Ground Operations, Launch and Ascent Thermal Analysis using Thermal Desktop

Presented By
Kan Yang
NASA Goddard Space Flight Center

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Overview

- Introduction to Launch and Ascent Thermal Analysis
  - Overview of early mission stages
- Thermal Analysis in Launch and Ascent Scenarios
  - Pre-Launch Ground Operations
    - Facility Storage
    - Gantry Operations
    - Pad Operations (Full Launch Vehicle Environmental Exposure)
    - Space Vehicle Cooling Inside Fairing
  - Launch and Ascent
    - Space Vehicle Inside Fairing during Launch
    - Space Vehicle with Free Molecular Heating and Motor Soakback after Fairing Separation
    - Space Vehicle after last stage motor separation
- Conclusions

Introduction to Ground Operations

- What environmental effects do you think these Launch Vehicles see on the pad?

Source: www.universetoday.com

- What environmental effects do you think this Launch Vehicle sees during the launch and ascent mission stages?

- More importantly, what do you think the spacecraft sees?

Source: www.nasa.gov

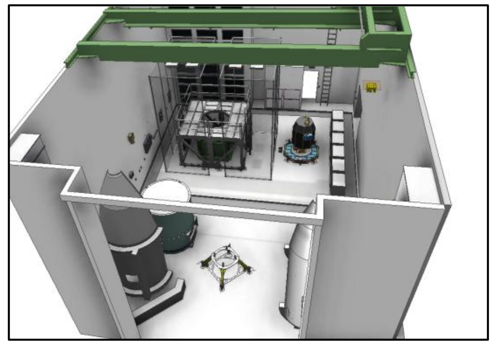
Why is Launch Analysis important?

- Ground operations and launch analysis can be crucial to the success of the mission
  - Analysis can ensure that launch vehicle (LV) and space vehicle (SV, i.e. spacecraft) do not exceed allowable temperature limits during early mission phases
  - Some components on LVs can be especially sensitive to heat and thermal stress: analysis can capture detailed temperature gradients on sensitive regions of LV
  - Results from ground operations models can be used to appropriately size air conditioning systems (mass flow rate, air inlet temperature) for gantry or storage facility
  - Results from ground operations models can determine how long LV/SV can be subjected to environmental heat before they need to move back to air conditioned environment: important for gantry roll-back operations, open gantry doors, and HVAC failures
  - Results from flight models can determine if SV needs any additional thermal blanketing/shielding during launch to keep components safe

Overview of Early Mission Phases

Transport of the Space Vehicle (SV) and launch vehicle (LV) to the processing facility

Testing/Integration of the LV and SV in the launch processing facility

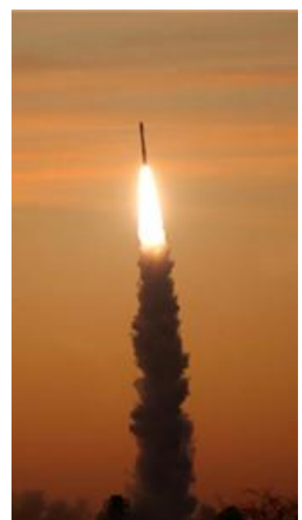


Transport of integrated LV components to gantry

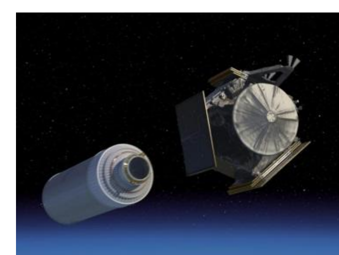
Stacking operations in the gantry

Pre-Launch / Pad Operations

Launch and Ascent



Fairing Separation and SV Separation



Source: http://easternshoredefensealliance.org/files/LADEEmoonmission.pptx, www.mfrtech.com, www.nasa.gov

Pre-Launch Ground Operations

Note: All thermal analysis performed with Thermal Desktop and SINDA/FLUINT

Nomenclature: SV – Space Vehicle
LV – Launch Vehicle

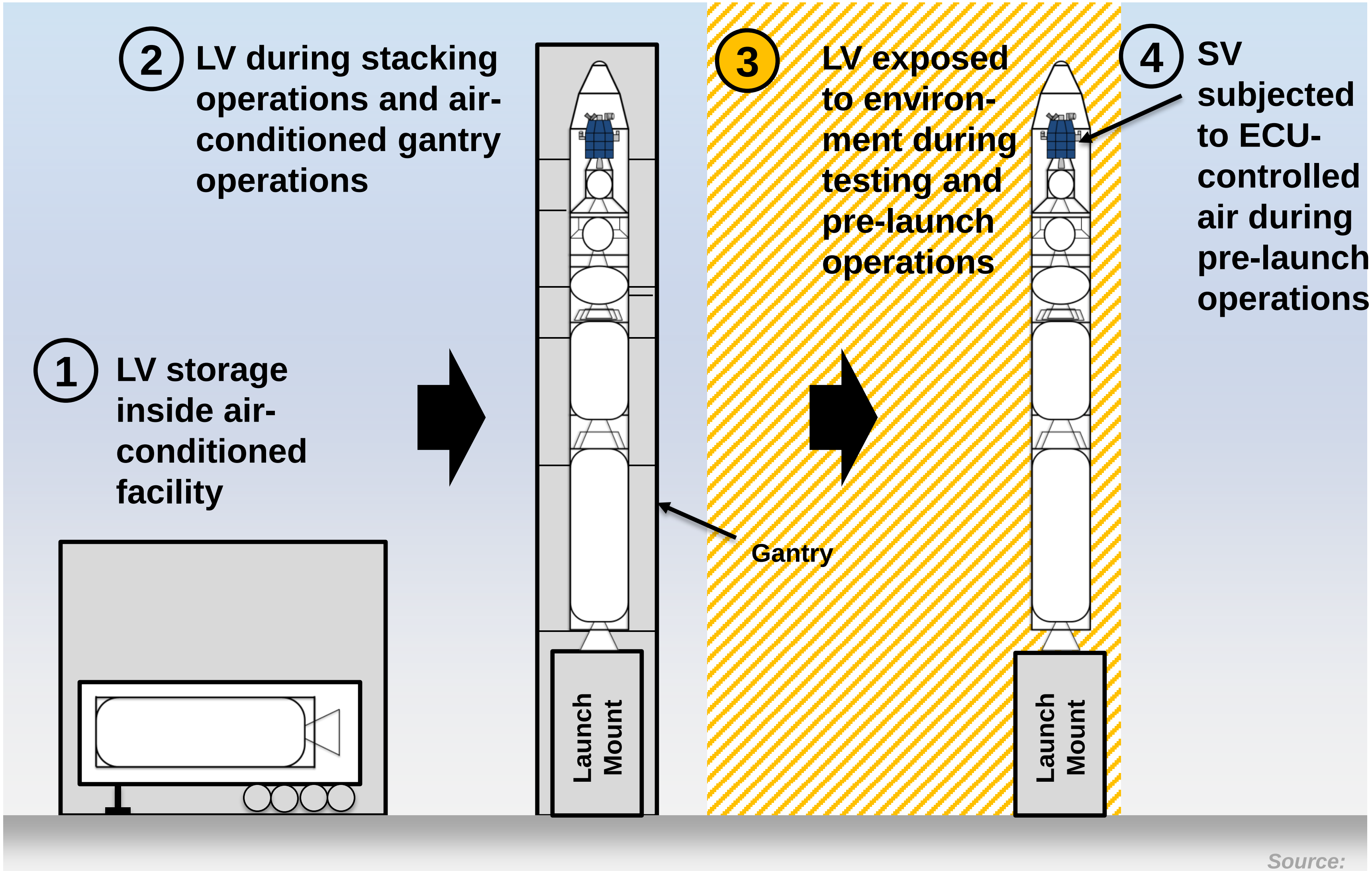
Disclaimer

The following is intended to be a basic introduction to Ground Ops, Launch and Ascent Analysis…

… however, it is not intended to cover all aspects of and methods for Launch Analysis, nor is the instructor an expert in the subject.

Please feel free to provide comments and ask questions

Common Pre-Launch Cases



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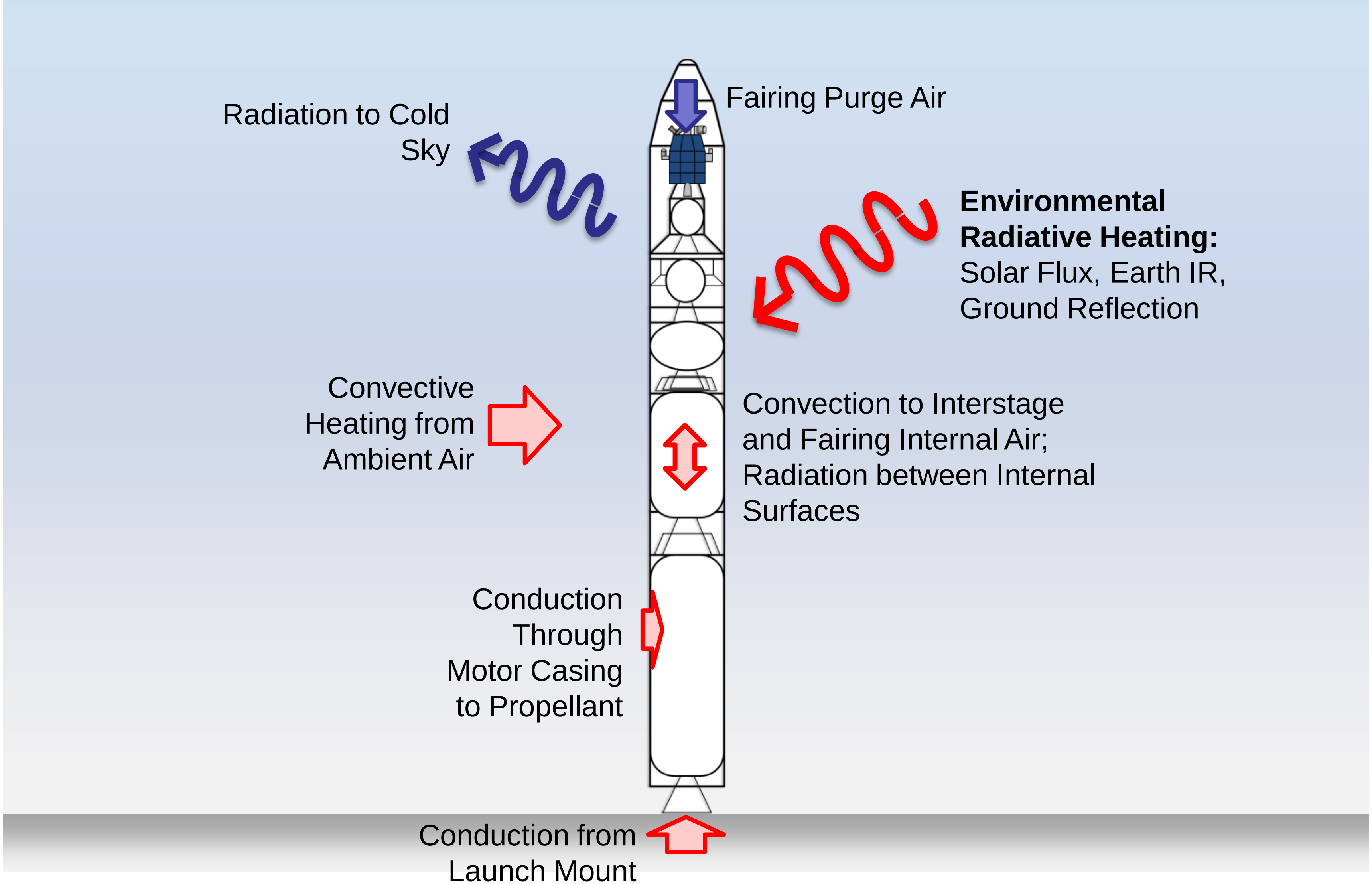
What are major heat flows in Ground Ops?



How would you go about modeling this?

1. **Two radiation analysis groups**

External Radks

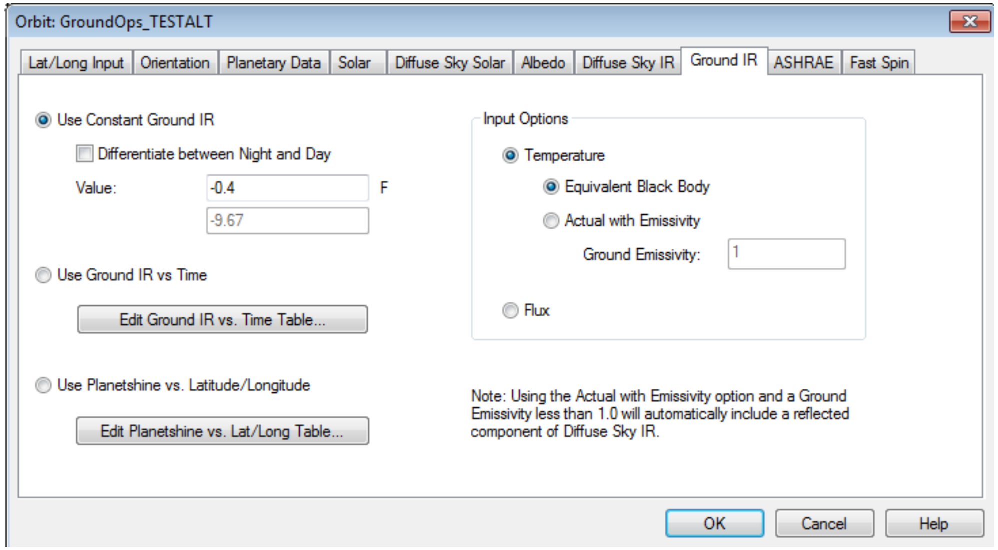
- Radiation couplings to “space” (diffuse sky temperature)
- Heat rates from Solar Flux, Earth IR, Radiative exchanges with ground

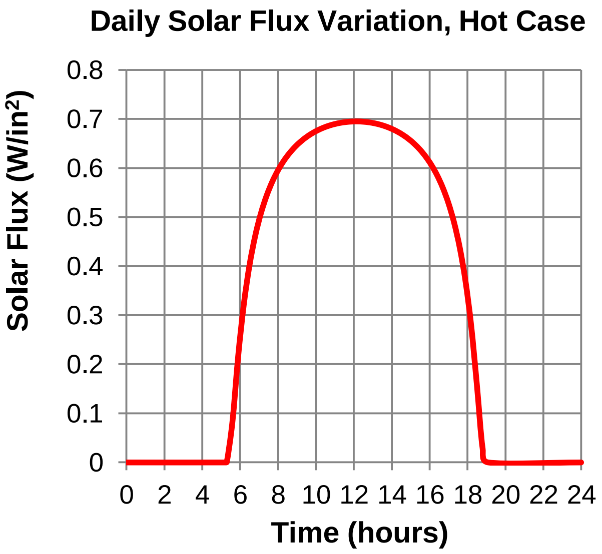
Internal Radks

- Radiation couplings for all internal components of LV
- Heat loads from any components generating internal heat during testing

Ground Ops Heat Rates in Desktop

- For Ground Ops, use Thermal Desktop Planetary Latitude/Longitude/Altitude List in Orbit Manager
  - Lat/Long Input: Use Lat/Long of Launch Site, 0 km Altitude, for entire runtime (orient spacecraft to +Z zenith)
  - Hot Case: use solar flux vs. time (determine daily variation of solar flux at launch location). For cold case: Solar = 0
  - Albedo: Use 0.35 in hot case, 0 in cold case
  - Diffuse IR based on cold sky temperature (discussed later)
  - Can use constant Ground IR with Ground Emissivity, or Ground IR vs. Time

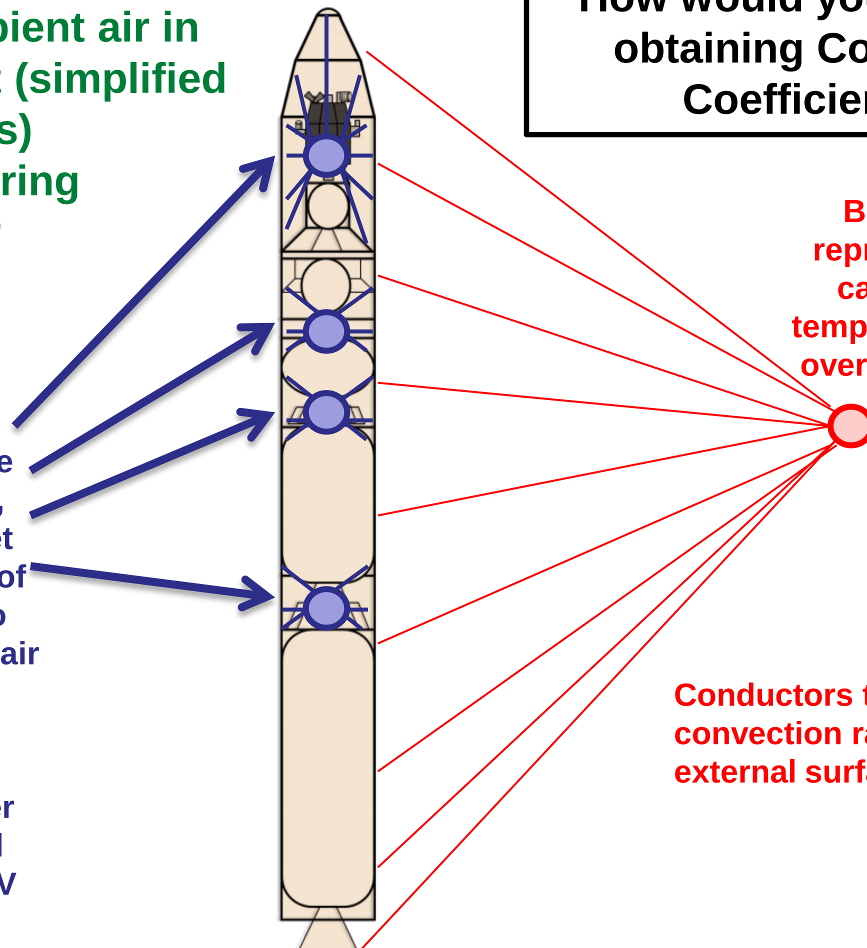




How would you go about modeling this?

1. Two radiation analysis groups
2. Convection from ambient air in external environment (simplified into linear conductors)
3. Convection inside fairing (simplified into linear conductors)

How would you go about obtaining Convection Coefficient, *h*?



One diffusion node per cavity (fairing, interstage, etc.) set with thermal mass of air inside cavity to represent stagnant air

(conductors to represent natural convection rate per area to all internal surfaces of each LV cavity)

Boundary Node representing worst-case ambient air temperature (may vary over time in transient runs)

Conductors to represent convection rate per area to all external surfaces of LV

Natural Convection Coefficient

- A value for the convection rate per area (convection coefficient) is needed to represent natural convective heat transfer with a simple linear conductor in Thermal Desktop:
  - The value of convection coefficient, h, for natural convection varies:
    - 5 W/m^2K can be assumed for still air inside cavity
    - Worst case ambient air convection scenarios:
      - Hot case: 35 W/m^2K if ambient air is hotter than LV
5 W/m^2K if ambient air is cooler than LV
      - Cold case: 35 W/m^2K if ambient air is cooler than LV
5 W/m^2K if ambient air is hotter than LV

Note: *launch locations are not always hot. Therefore, cold convection cases are relevant too. Examples of cold environments include:*

Kodiak Launch Complex Alaska

Baikonur Cosmodrome Kazakhstan

Orbital Sciences Corp. Pegasus Launch System

Variation in Air Temperature

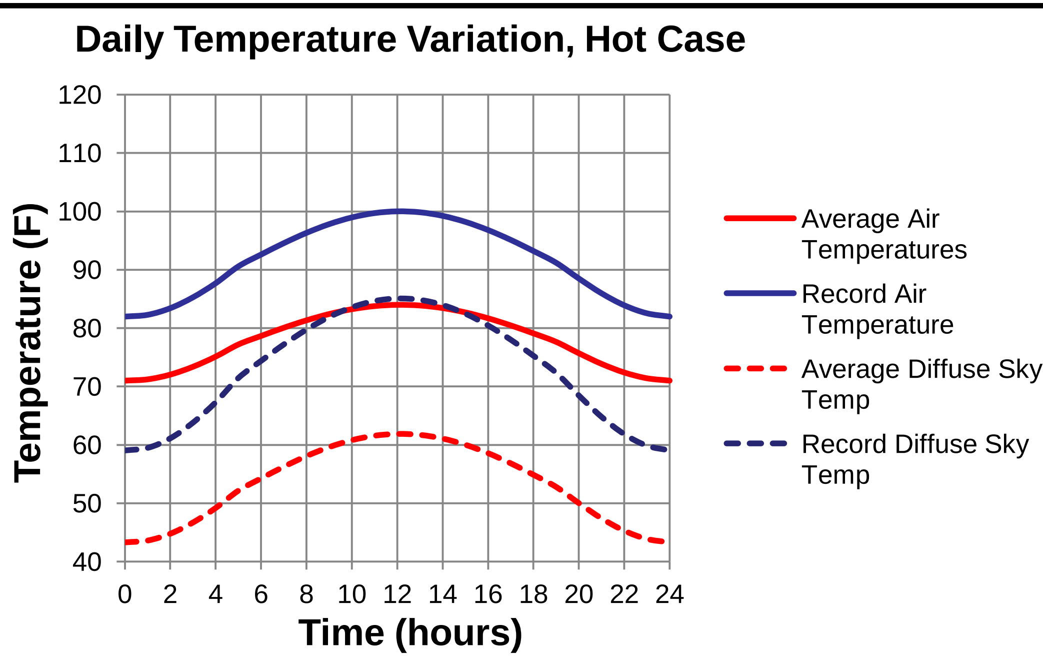
- For ambient air temperature, set representative boundary node to diurnal variation of air temperature (**record cold** / **record hot** for location)
- For radiation to diffuse sky: create boundary node with same submodel name and node number as SPACE boundary node in external radiation group, i.e. “SPACE.1” or “SPACE.9999”, vary boundary node temperature vs. time with diffuse sky temperature

One possible way to find diffuse sky temperature is with the Swinbank Equation:

$$T_{sky} = 0.0552(T_{air,amb})^{1.5}$$

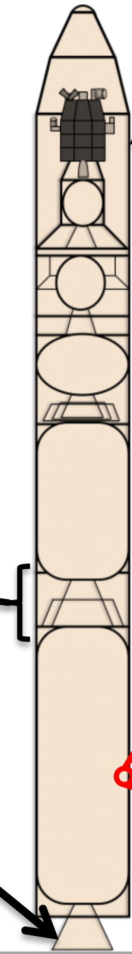
T_{sky}	Diffuse Sky Temperature*
$T_{air,amb}$	Ambient Air Temperature*

*On absolute temperature scale



How would you go about modeling this?

1. Two radiation analysis groups
2. Convection from ambient air in external environment (simplified into linear conductors)
3. Convection inside fairing (simplified into linear conductors)
4. Model areas on LV with large expected temperature gradients in higher detail

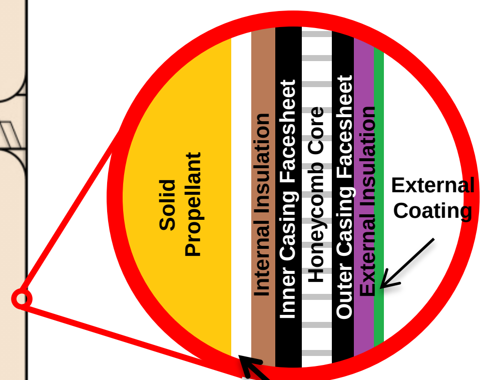


Capture **fairing insulation** well, especially properties of **acoustic blanket** (this provides your SV the most isolation from the environment)

Thermal properties of **interstage rings** must be captured in detail since they are low thermal mass

Nozzles have very little thermal mass and **do not need to be modeled in large detail**: have very little impact on overall system temperature

Motor Casing to Propellant

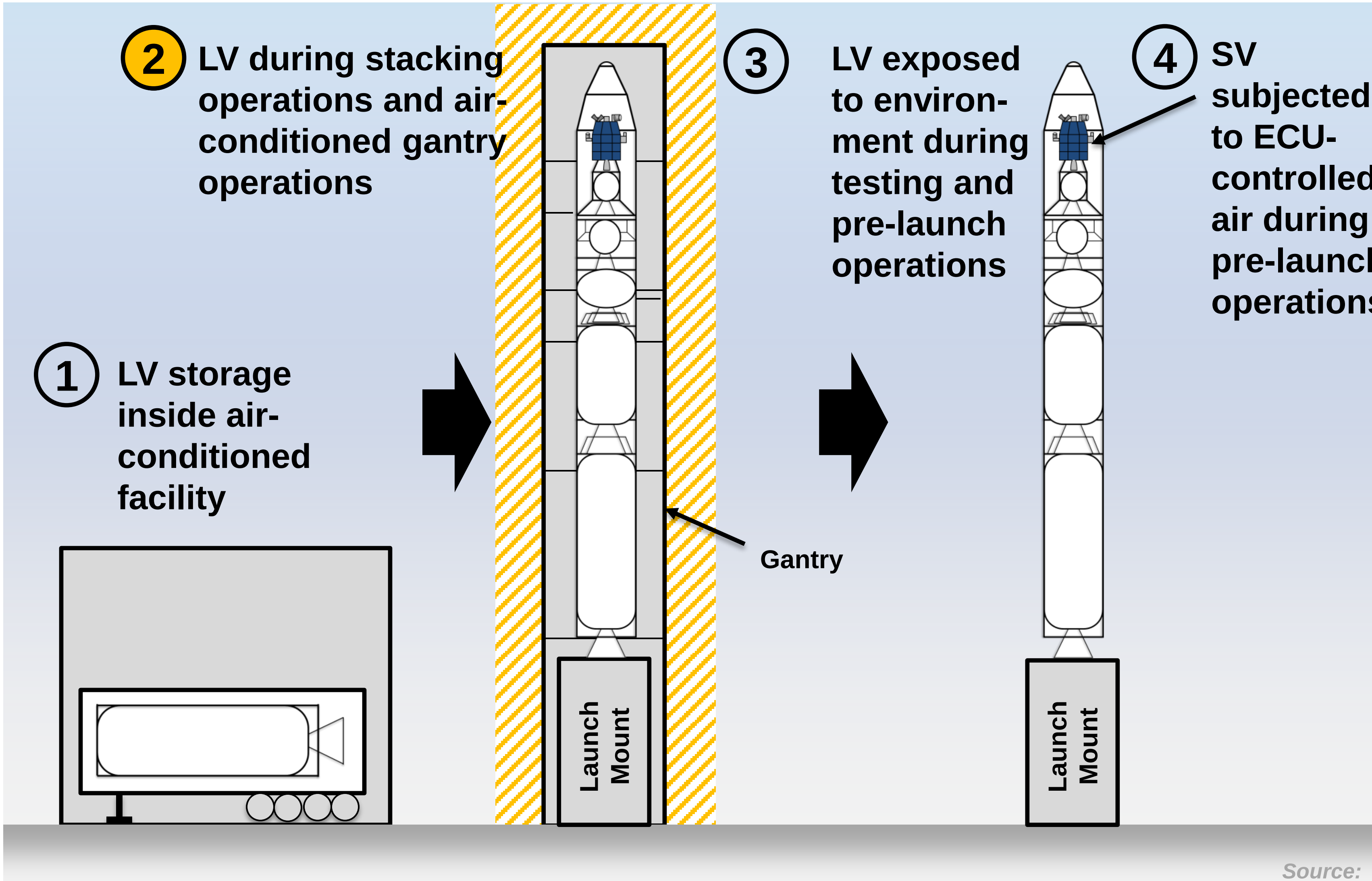


Contactor to represent bond line

Note: for solid propellant motors, modeling of the **bond line between propellant and motor** casing is crucial since this is usually a thermally sensitive component

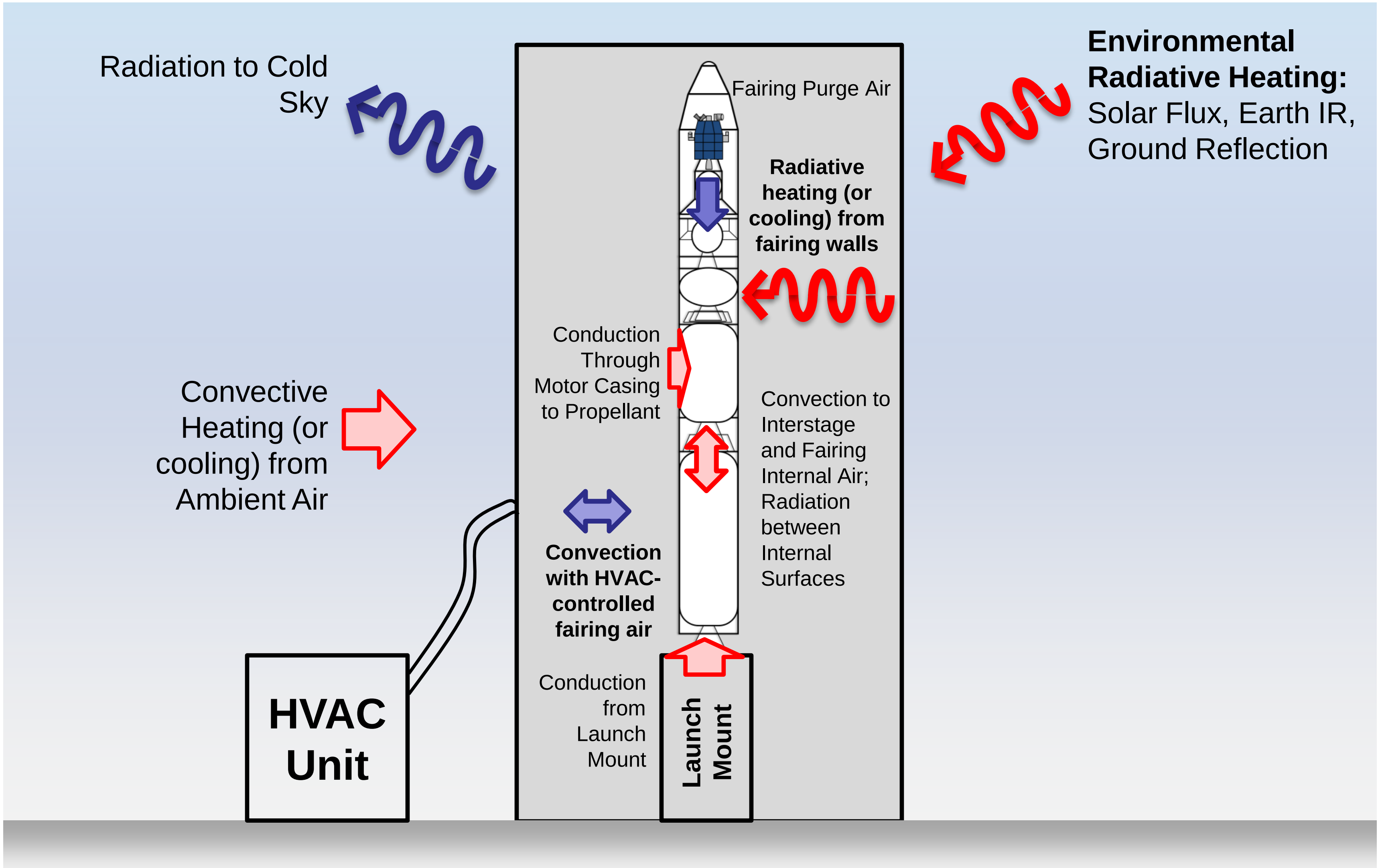
For liquid propellant motors, **empty propellant tank is most conservative assumption**. When fueled, liquid propellant can be represented by diffusion node with thermal capacitance of fuel, tied to internal surface of tank with conductors

Common Pre-Launch Cases



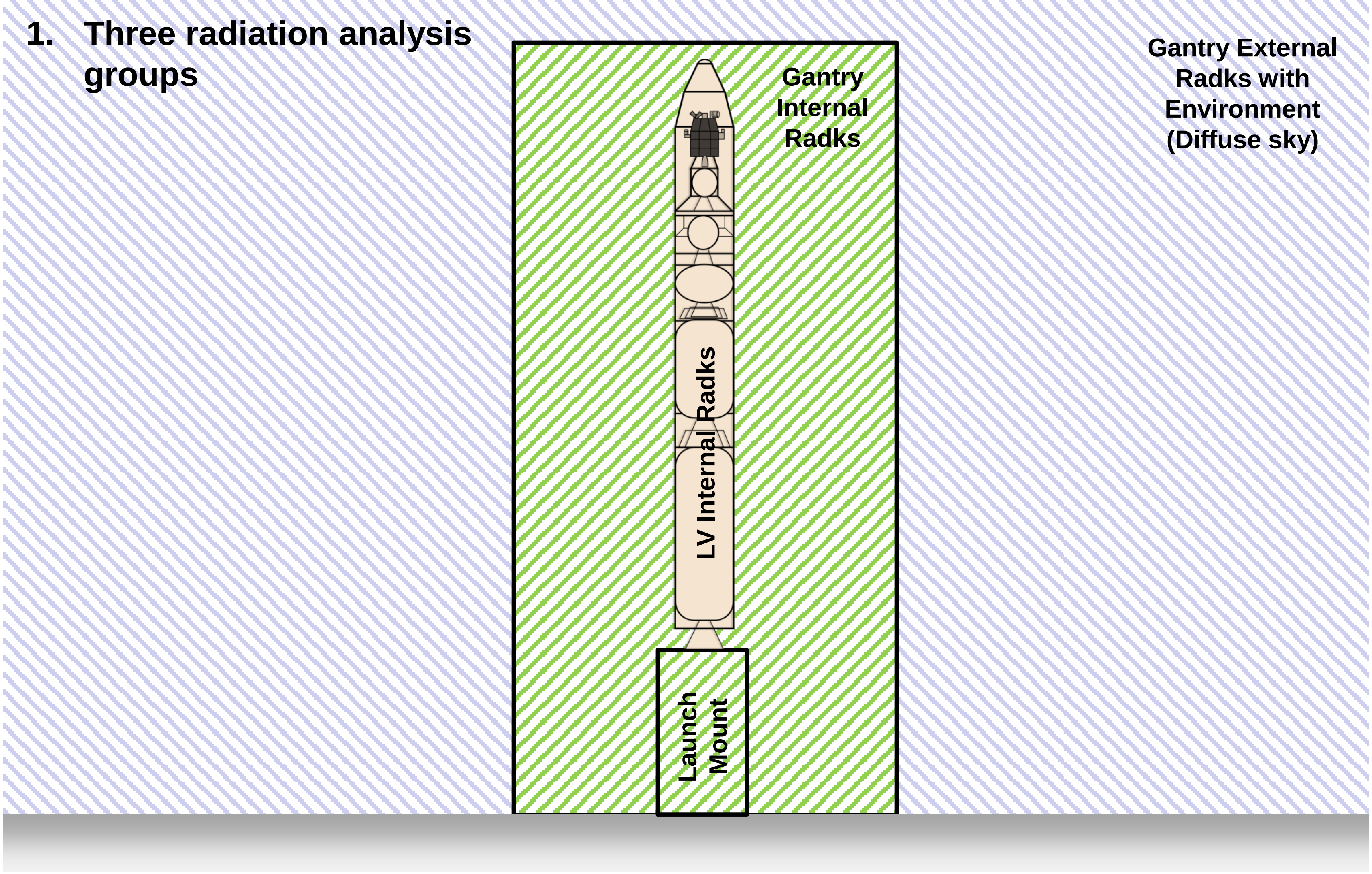
Source: http://easternshoredefensealliance.org/files/LADEEmoonmission.pptx

What if the LV was in the Gantry?



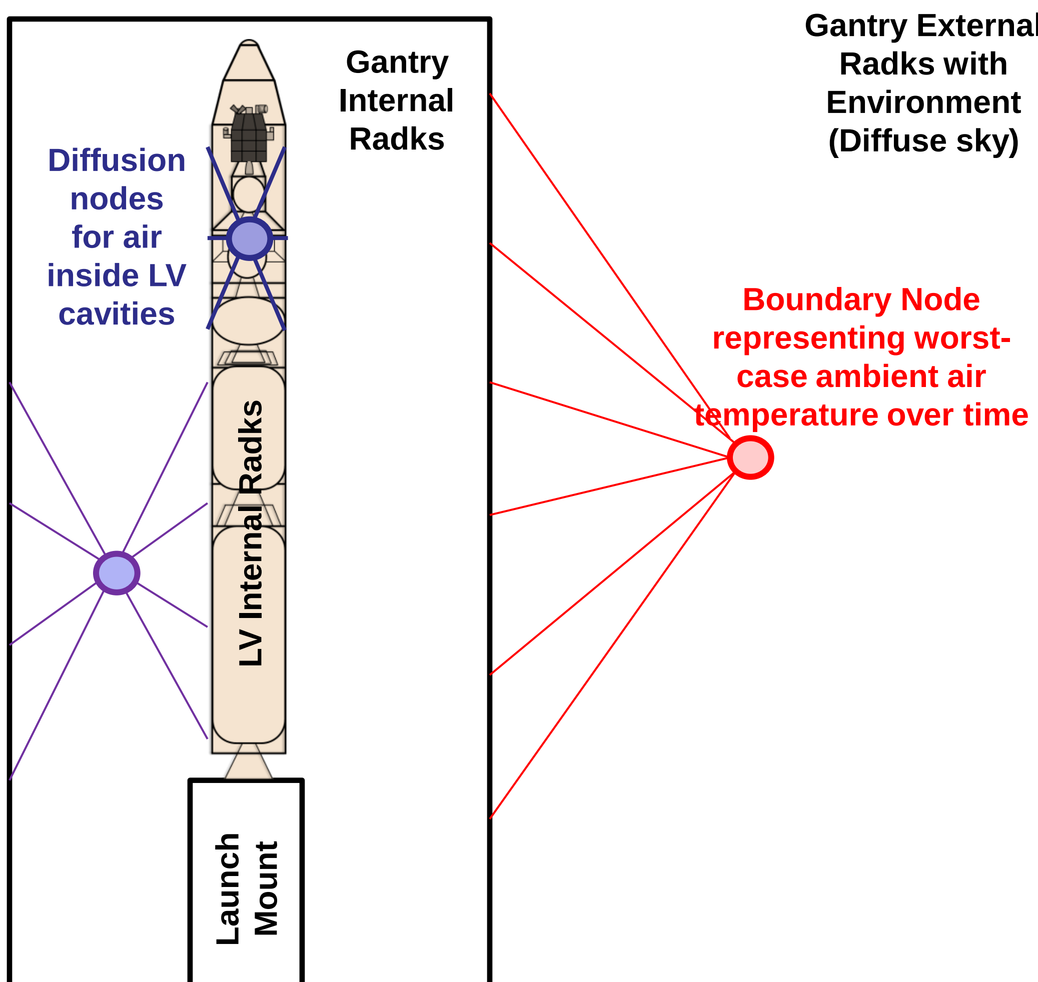
Modeling Gantry Case

1. **Three radiation analysis groups**



1. Three radiation analysis groups
2. Three convection sources:
   1. Natural convection from ambient air
   2. Forced convection from Gantry HVAC
   3. Natural convection of air in LV cavities

Boundary node for worst-case heated/cooled Gantry HVAC air
(use of FLUINT is also possible, but not required for practical, first-cut analysis)



How would you go about obtaining the forced air Convection Coefficient, *h*, from the gantry HVAC?

Forced Convection Coefficient, *h*

- For forced convection per area, you will need to obtain the convection coefficient
  - The value of convection coefficient, h, is calculated from:

$$h = \frac{k\,Nu}{D}$$

where:		
	k	Thermal conductivity
	D	Characteristic dimension
	Nu	Nusselt Number, $Nu = 0.23Re^{0.8}Pr^{0.4}$
		(Dittus-Boetler Equation)

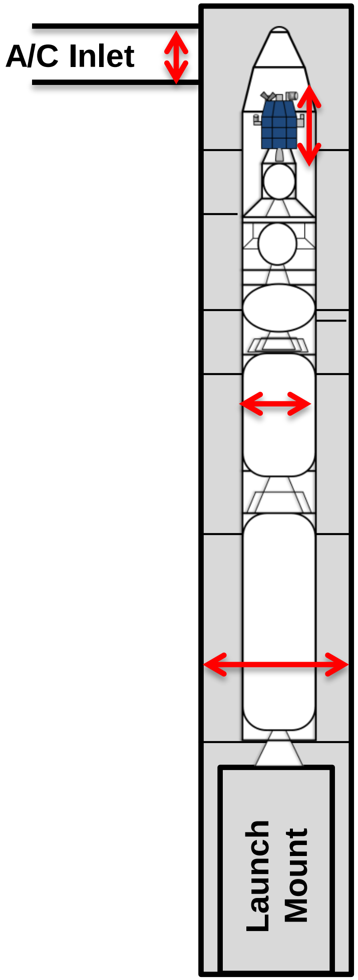
$$Re = \frac{\rho v D}{\mu} = \frac{\rho \dot{v} D}{A_c \mu}$$

$$Pr = \frac{C_p \mu}{k}$$

A_c	Cross sectional area of duct
C_p	Specific heat
D	Characteristic dimension
h	Convection coefficient
k	Thermal conductivity
$\dot{m}$	Mass flow rate
μ	Dynamic viscosity of fluid
Nu	Nusselt Number
Pr	Prandtl Number
Re	Reynolds Number
ρ	Density
v	Velocity
$\dot{v}$	Volumetric flow rate

Characteristic Dimension, *D*

- Which characteristic dimension do you pick?



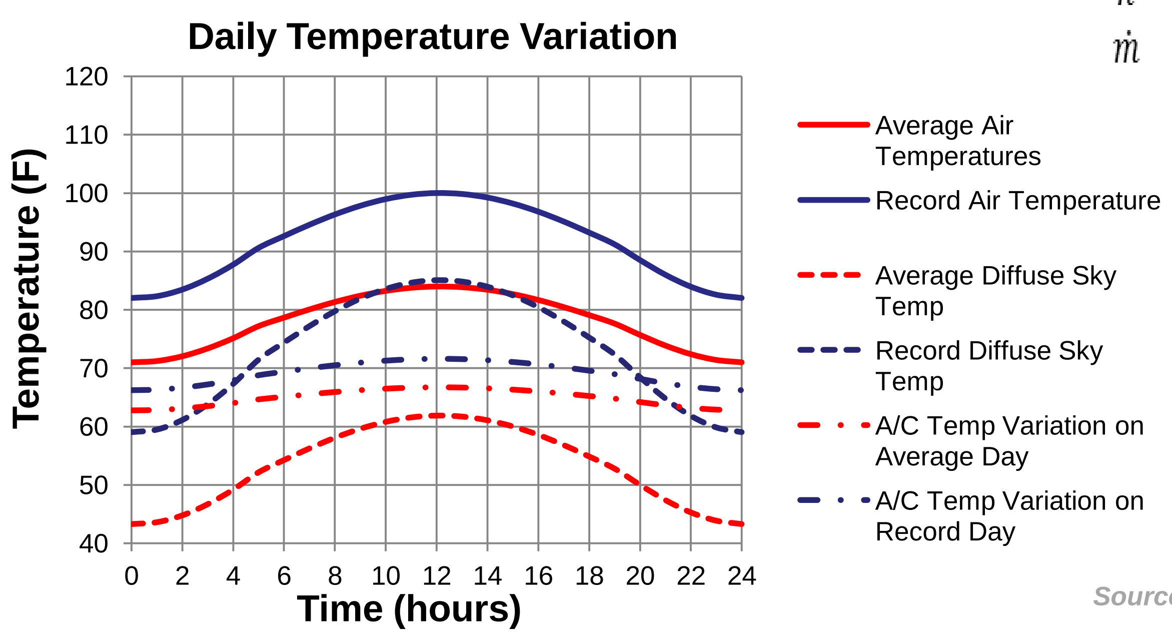
  - Many possible characteristic dimensions to pick from
  - However, due to the large scales of the LV or SV dimensions, the magnitude is much larger than the velocity of the incoming air and produces a low Re.
  - For conservatism, you may want to pick the largest characteristic dimension. However, if the resultant *h* is very small, then you can just assume lowest value of natural convection (5 W/m^2K)
  - For gantry-level flows, LV diameter can be a good characteristic dimension to pick. For fairing-level flows, longest SV bus cross-sectional dimension can be a good characteristic dimension.

Forced Convection Coefficient, *h*

- However, the variation in ambient air temperature also affects the temperature of the conditioned air as it travels from the HVAC to the gantry
  - Temperature at the exit of the air duct can be calculated with:

$$T_{exit} = T_{ambient} - (T_{ambient} - T_{inlet})e^{-\frac{hA_s}{\dot{m}C_p}}$$

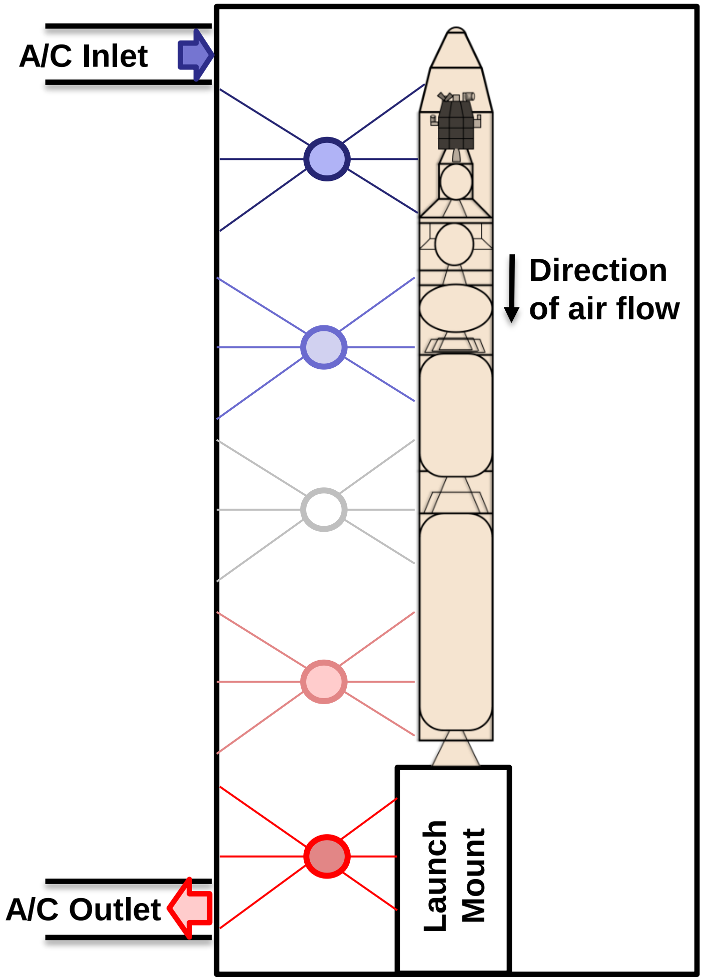
A_s	Cross sectional area of duct
C_p	Specific heat
h	Convection coefficient
$\dot{m}$	Mass flow rate



Source: NASA WFF, TASC, OSC

Forced Convection Coefficient, *h*

- The same equation from the previous slide can be used to calculate the increase (or decrease, in cold case) of HVAC air temperature inside the gantry
  - External surfaces on LV can be grouped by height and tied to different boundary nodes (that represent gradient of air temperatures) along height of gantry



Daily Double

THIS IS THE MOST IMPORTANT FACTOR FOR ISOLATING THE LAUNCH VEHICLE INSIDE THE GANTRY FROM EXTERNAL ENVIRONMENTAL LOADING

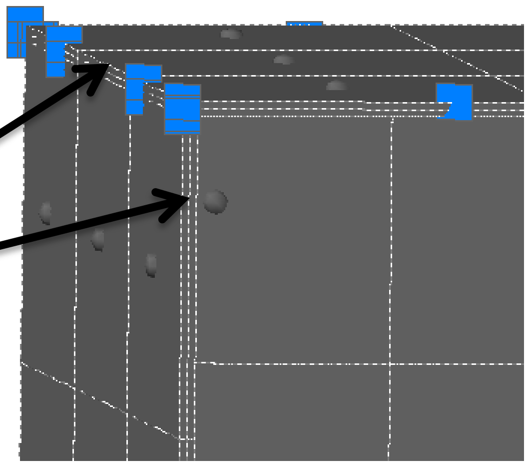
WHAT IS GANTRY INSULATION?

WHAT IS CONDITIONED AIR FROM HVAC?

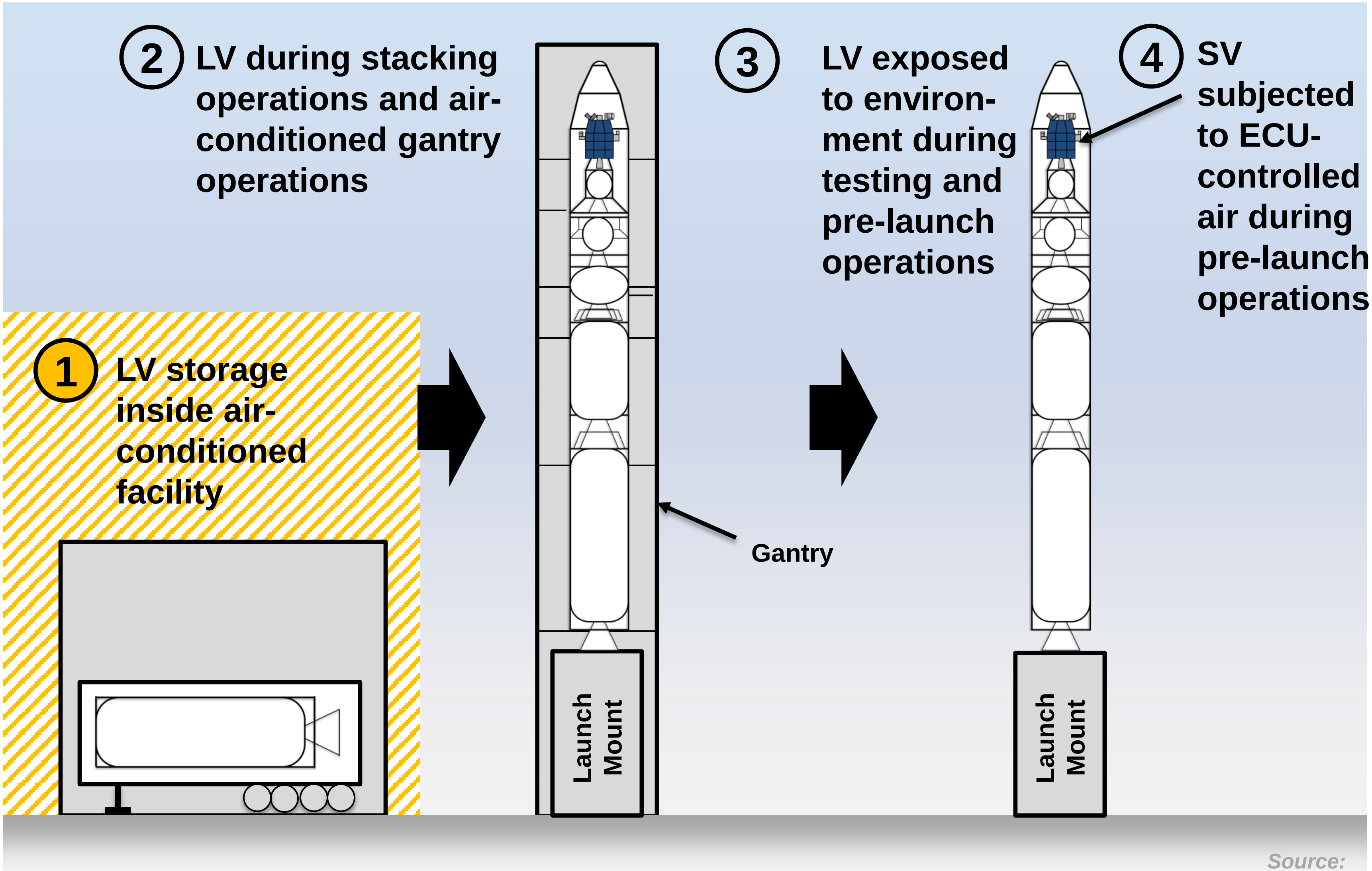
Gantry / Facility Insulation

- For most cases, facility insulation is much more important at isolating LV from environment than HVAC air
  - HVAC Air has minimal effect on dampening the environmental loading
  - Facility insulation (R-value) has **enormous** effect in blocking out radiative and convective heating from the environment
    - R-value given in **US** insulation spec sheets is in ft^2·ºF·(hr/BTU)
    - R-value given in **SI** insulation spec sheets is in m^2·K/W
  - To obtain thermal conductivity: ***k = (Unit Thickness)/(R-value)***
    - (For most spec sheets: unit thickness in inches for **US**, mm for **SI**)
  - For a typical facility, the insulation through-thickness thermal conductivity is on the order of 10^{-2} W/m-K

Model facility walls as solid geometries. Make sure you have enough through-thickness nodalization for the facility walls in your thermal model to capture appropriate temperature gradients



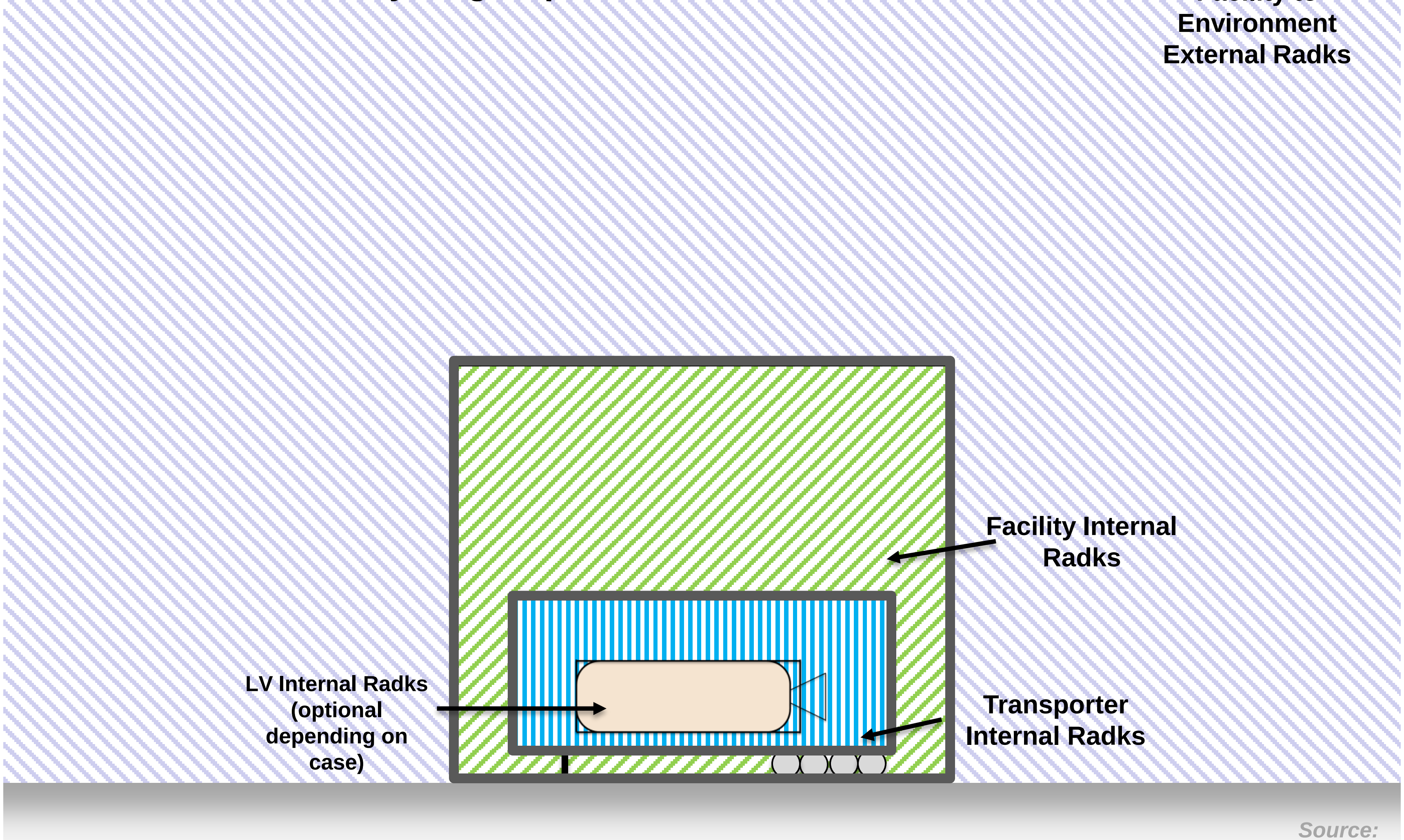
Common Pre-Launch Cases



Source: http://easternshoredefensealliance.org/files/LADEEmoonmission.pptx

Modeling Facility Storage Case

1. **Four radiation analysis groups**

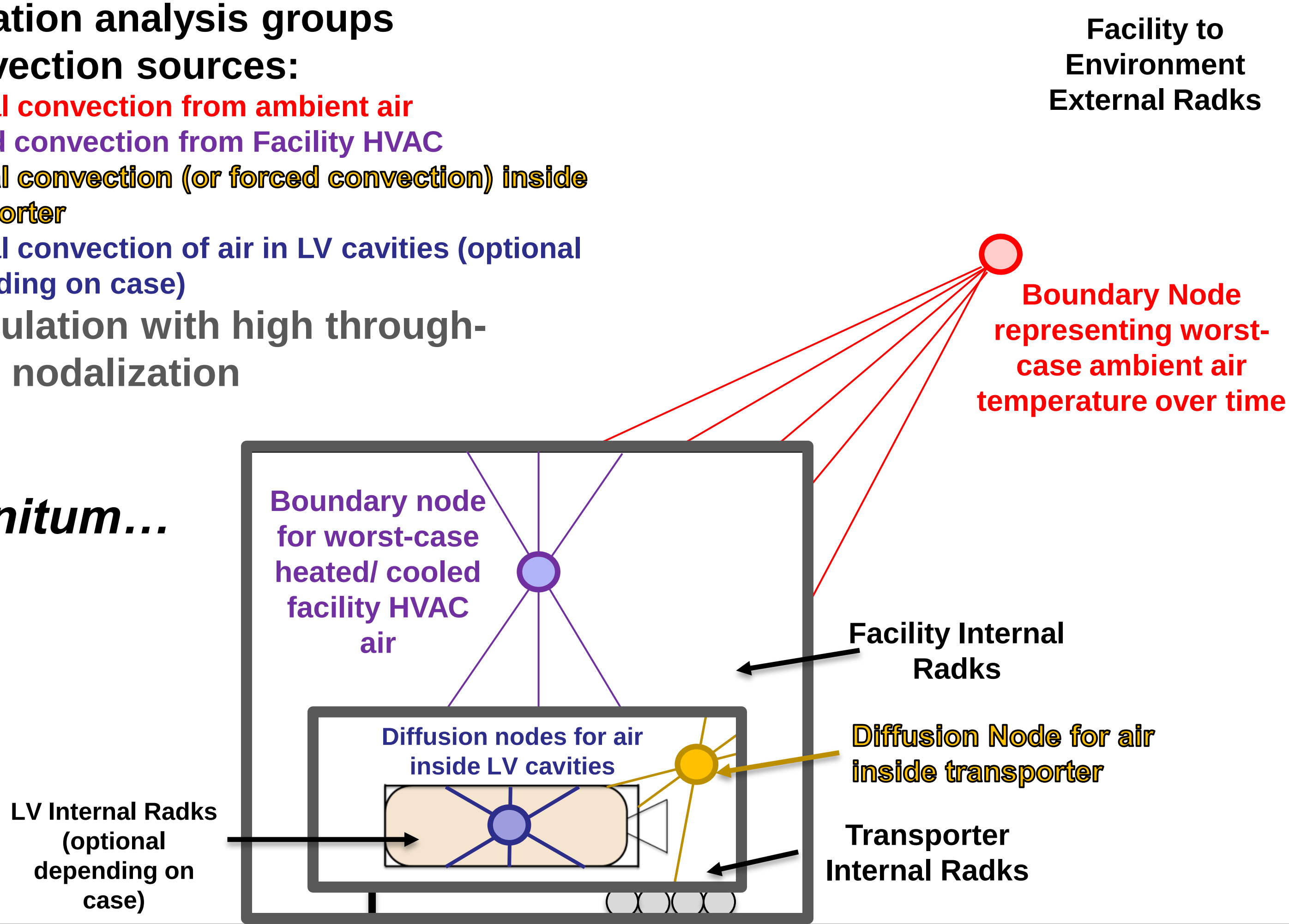


Source: http://easternshoredefensealliance.org/files/LADEEmoonmission.pptx

Modeling Facility Storage Case

1. Four radiation analysis groups
2. Four convection sources:
   1. Natural convection from ambient air
   2. Forced convection from Facility HVAC
   3. Natural convection (or forced convection) inside transporter
   4. Natural convection of air in LV cavities (optional depending on case)
3. Model insulation with high through-thickness nodalization

Ad infinitum…



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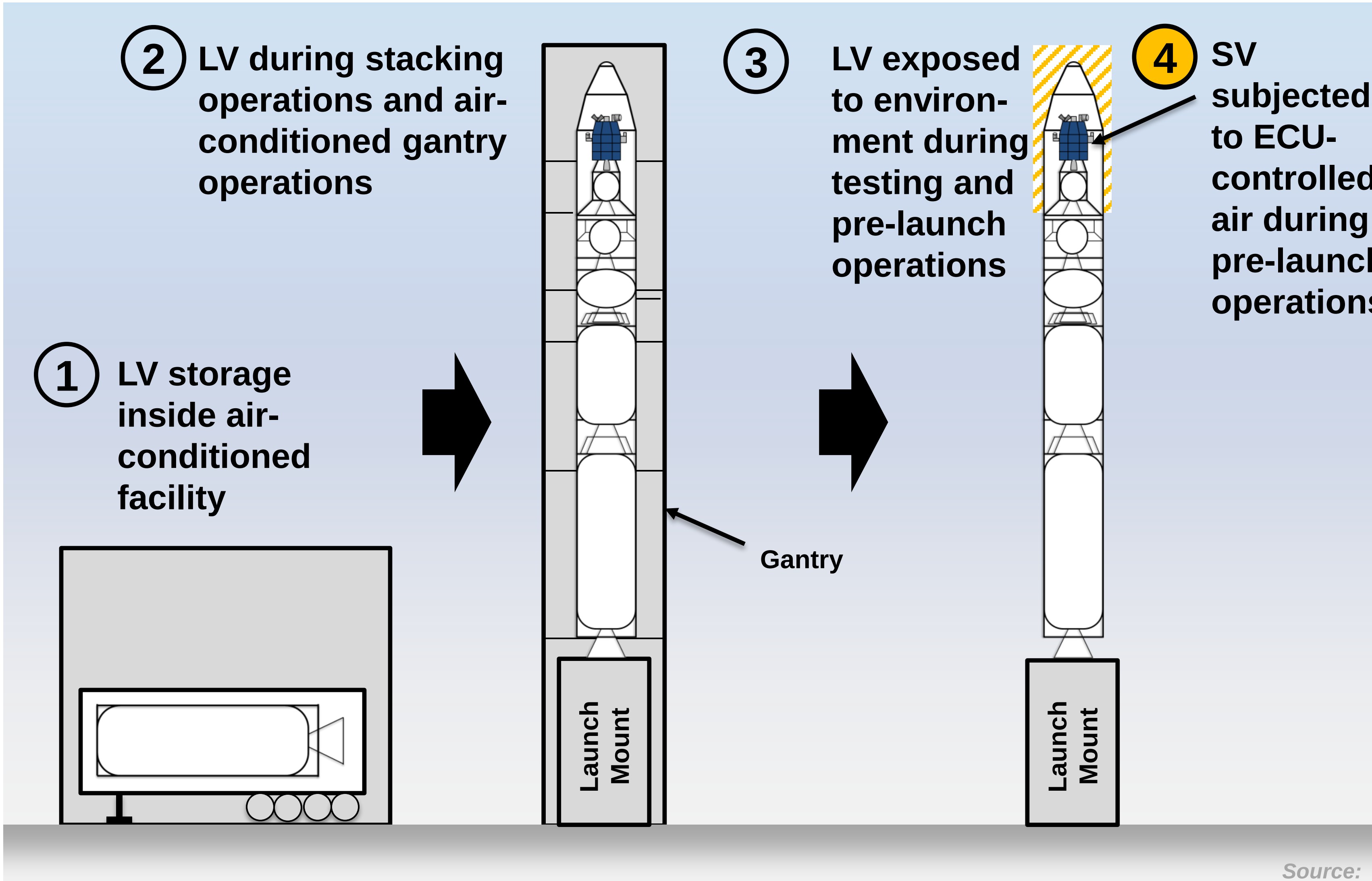
Common Pre-Launch Cases



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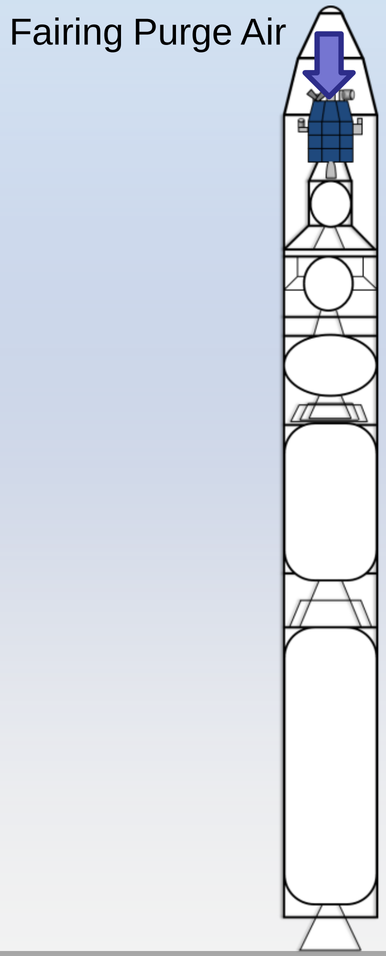
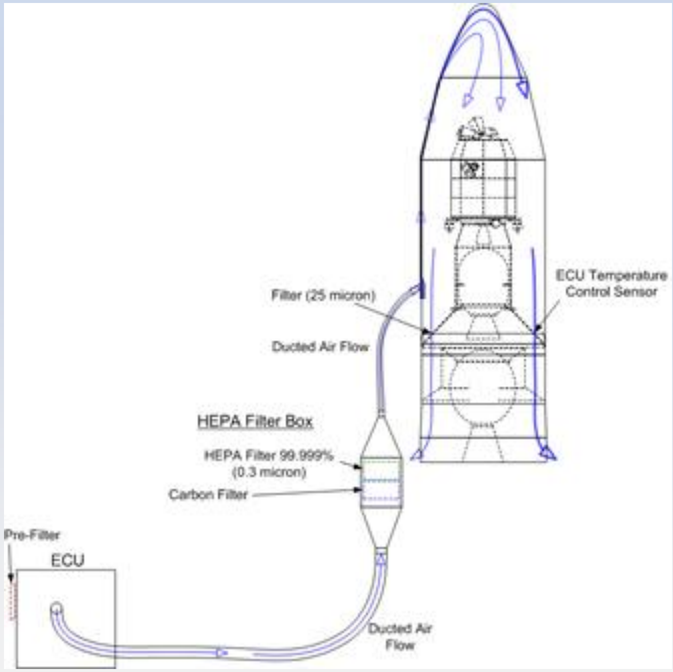
For Fairing Flows…



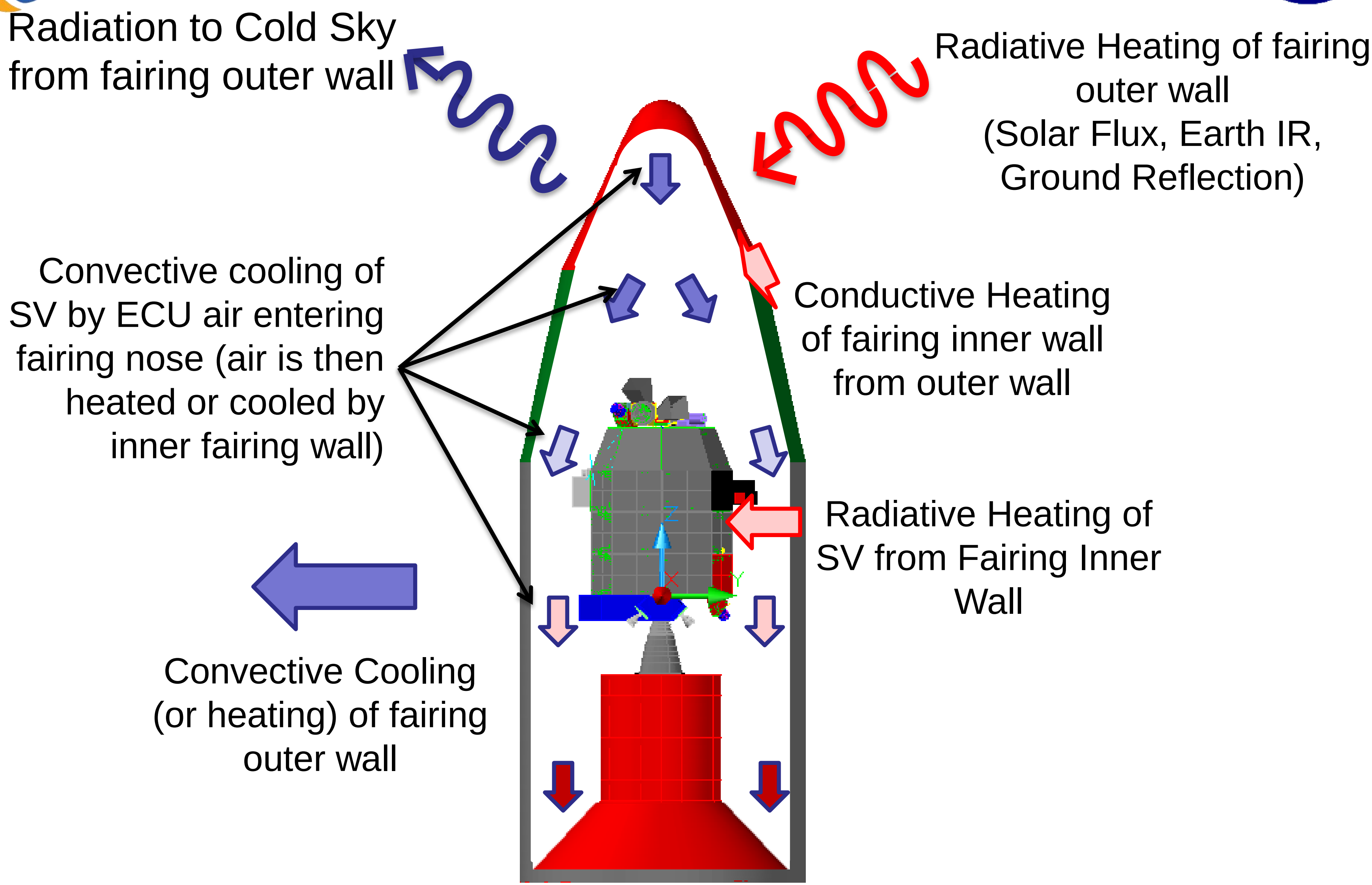
Fairing air is typically maintained by an Environmental Control Unit (ECU)

- **Ducts air-conditioned, humidity-controlled air to nose of the fairing**
- **Air travels through the fairing and typically vents out of bottom of fairing or interstage**



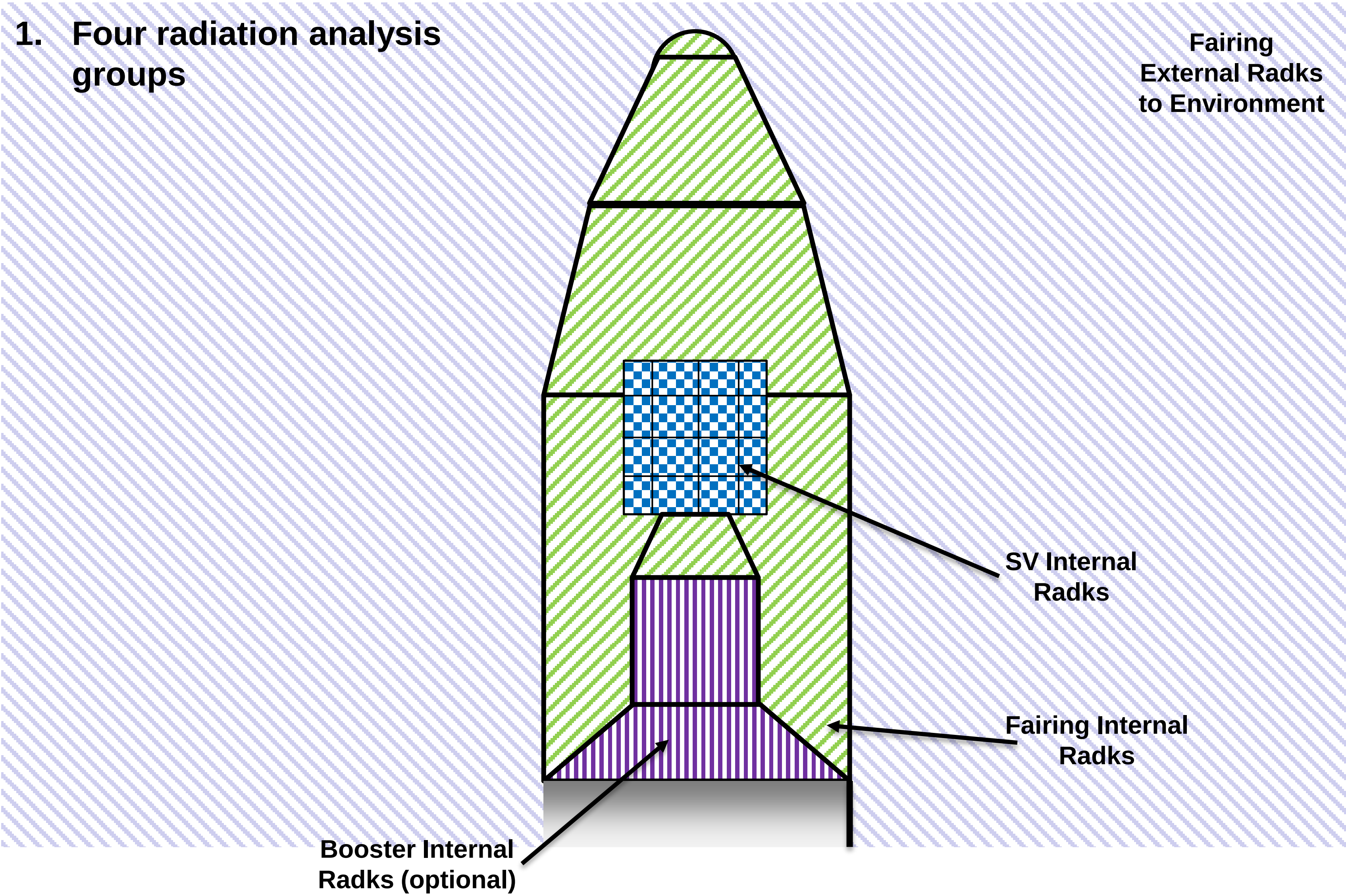
Source: OSC

SV Inside fairing with ECU cooled air



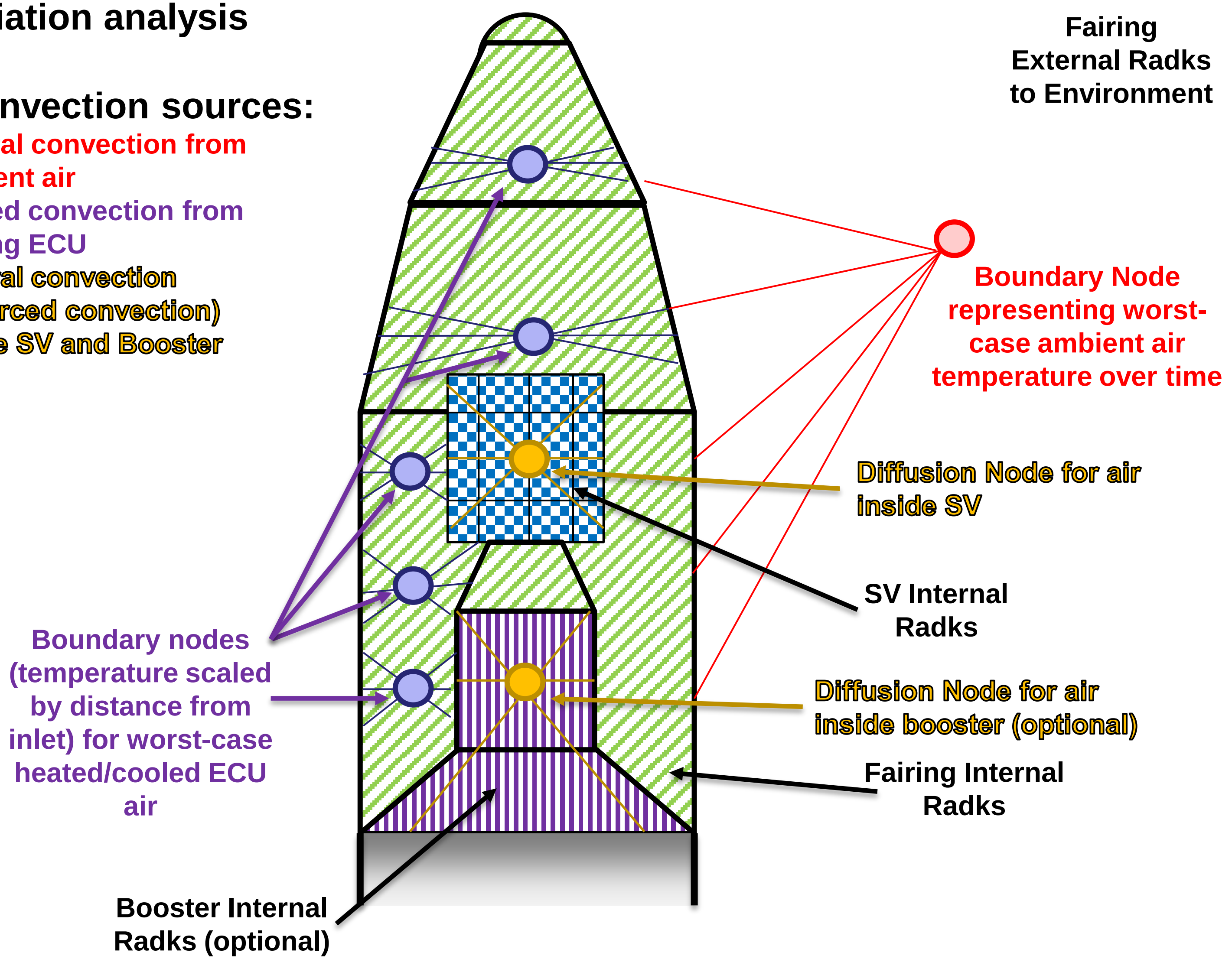
Modeling SV Inside Fairing

1. **Four radiation analysis groups**



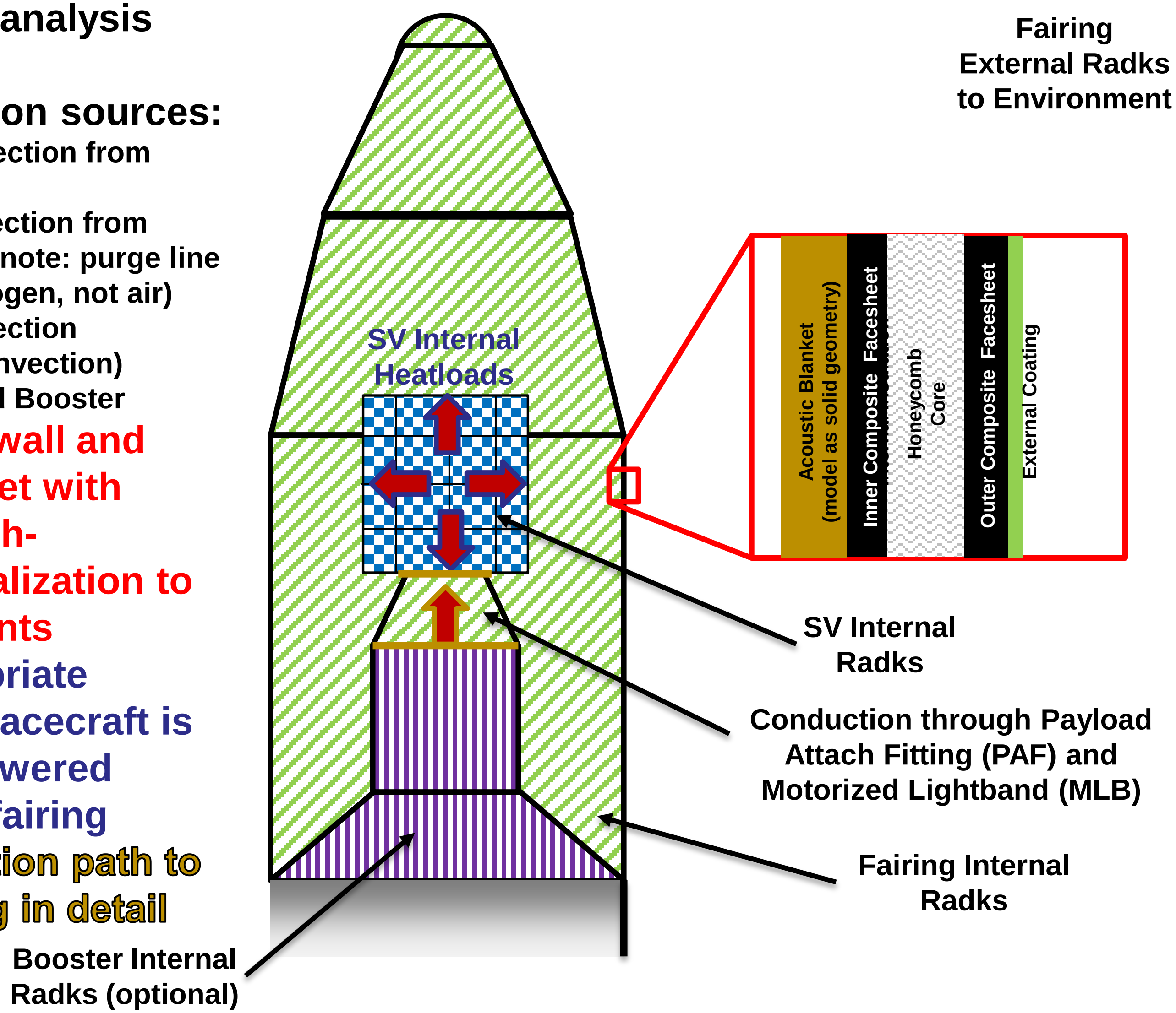
Modeling SV Inside Fairing

1. **Four radiation analysis groups**
2. **Three convection sources:**
   1. Natural convection from ambient air
   2. Forced convection from Fairing ECU
   3. Natural convection (or forced convection) inside SV and Booster



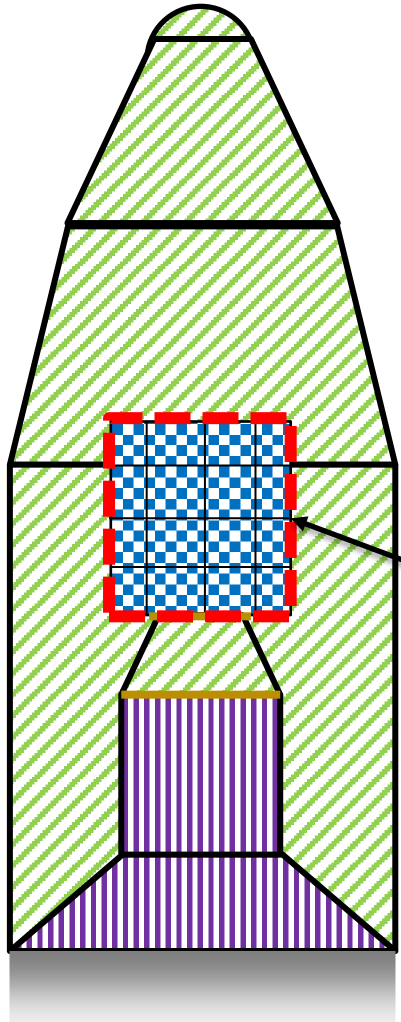
Modeling SV Inside Fairing

1. Four radiation analysis groups
2. Three convection sources:
   1. Natural convection from ambient air
   2. Forced convection from Fairing ECU (note: purge line may use nitrogen, not air)
   3. Natural convection (or forced convection) inside SV and Booster
3. Model Fairing wall and acoustic blanket with enough through-thickness nodalization to capture gradients
4. Impose appropriate heatloads if spacecraft is undergoing powered testing inside fairing
5. Model conduction path to LV adapter ring in detail



Modeling SV Inside Fairing

1. **Four radiation analysis groups**
2. **Three convection sources:**
   1. **Natural convection from ambient air**
   2. **Forced convection from Fairing ECU (note: purge line may use nitrogen, not air)**
   3. **Natural convection (or forced convection) inside SV and Booster**
3. **Model Fairing wall and acoustic blanket with enough through-thickness nodalization to capture gradients**
4. **Impose appropriate heatloads if spacecraft is undergoing powered testing inside fairing**
5. **Model conduction path to LV adapter ring in detail**



Fairing and Booster model ~3000 nodes

6. **MLI is treated differently in launch cases**
   - replace e* with k* term

MLI in Ground Operations

- In Ground Ops, radiation is no longer the most dominant the heat transfer method in blankets: conduction / convection takes over ➔ use k* term instead of e*
- k* represents effective conduction through gas layer in blanket. Therefore, conductance through blanket is:

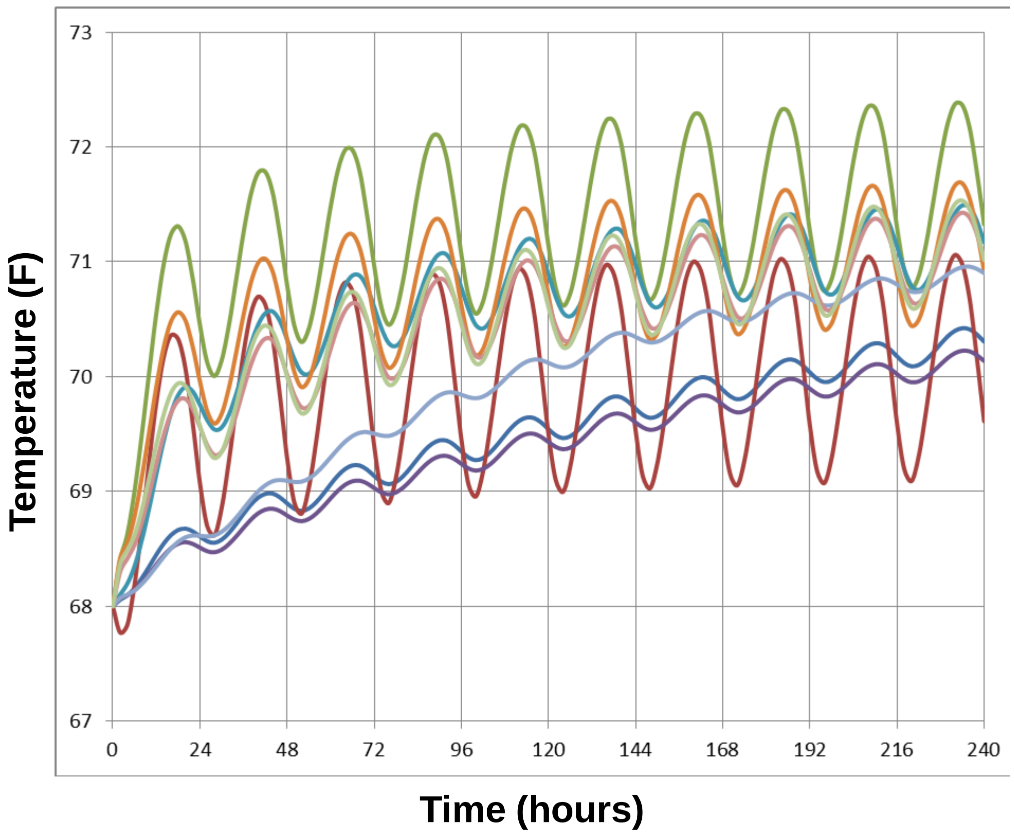
$$G_{blanket} = (k^*)\frac{A}{L}$$

A	Blanket area
$G_{blanket}$	Conductance of blanket
k^*	Thermal conductivity of gas used
L	Thickness of blanket (typically assumed 1/8")

during launch

Example Ground Ops Temperature Profile

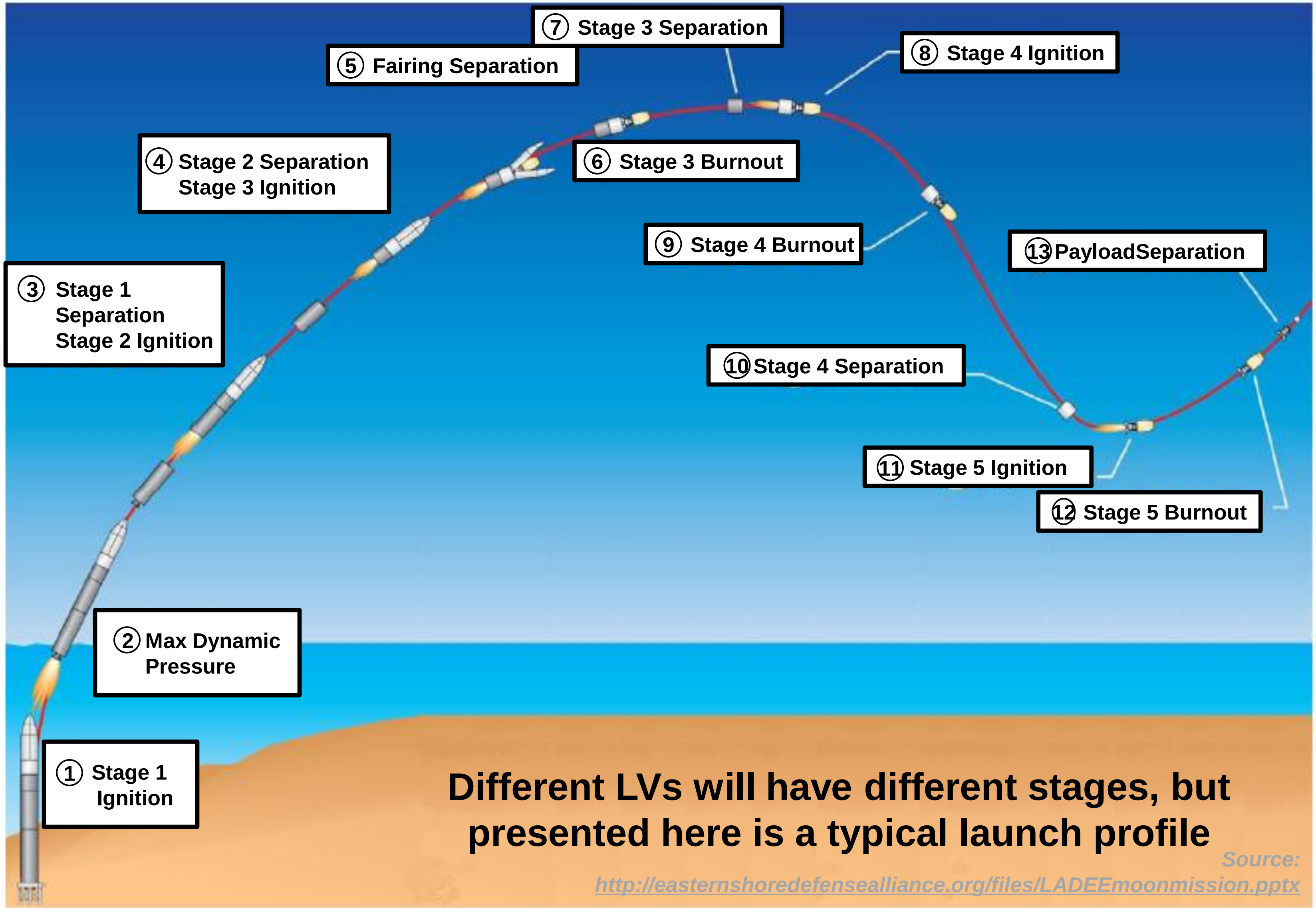
- Solution converges from initial temperature to a fixed diurnal variation around an average temperature



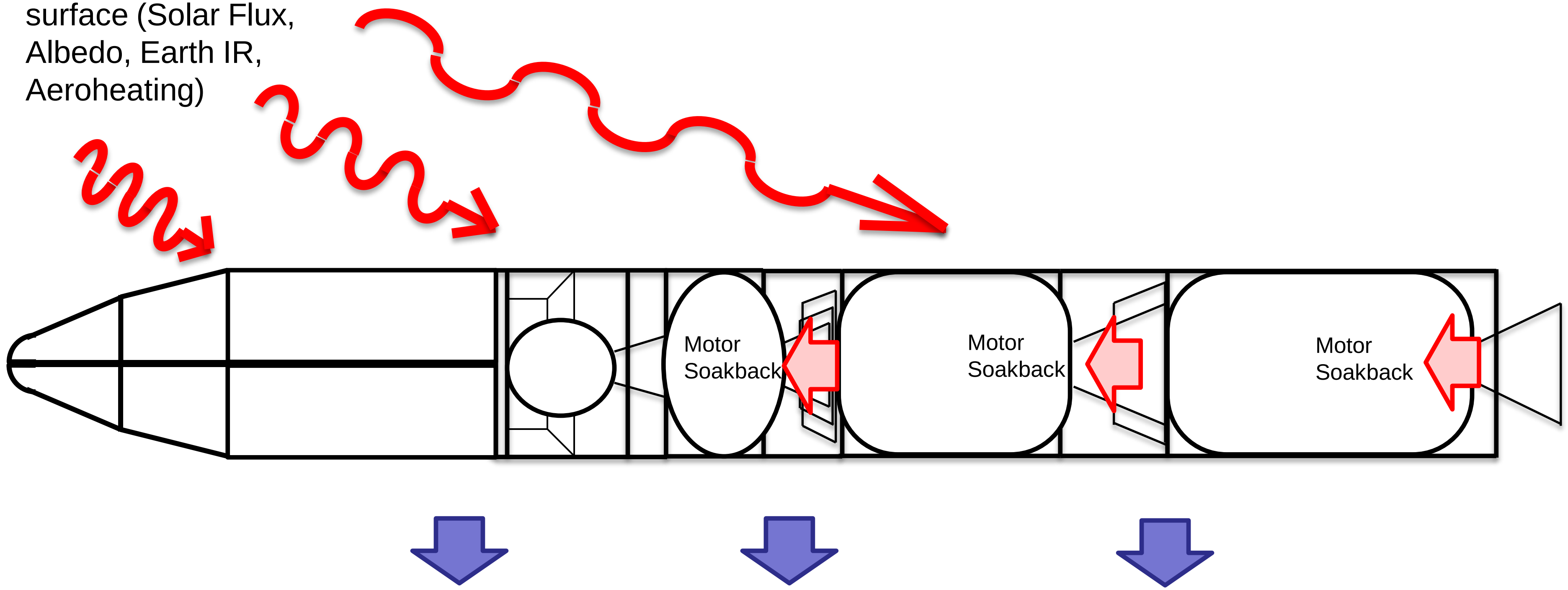
Launch and Ascent Mission Phases

Note: All thermal analysis performed with Thermal Desktop and SINDA/FLUINT

Typical Launch Timeline



Heating of LV external surface (Solar Flux, Albedo, Earth IR, Aeroheating)

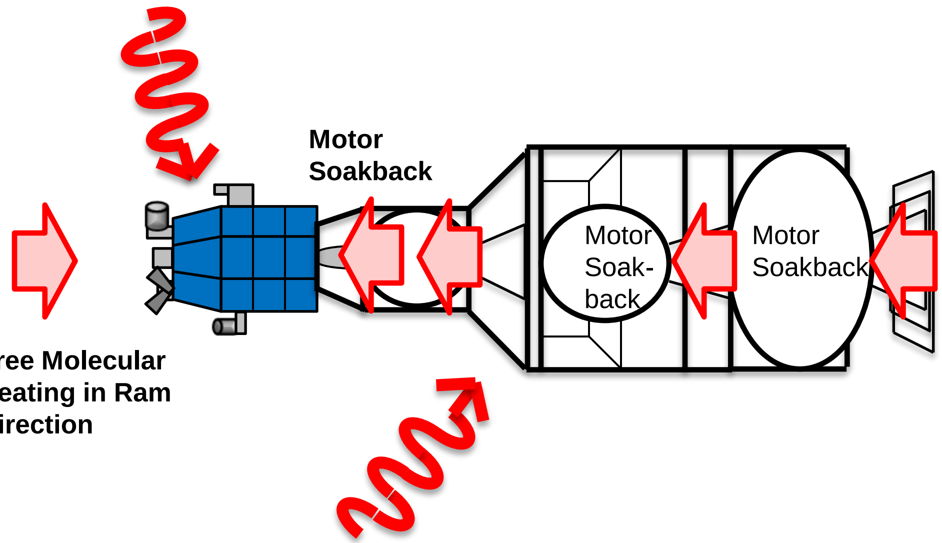


Convection to stagnant air (diminishes with loss of atmospheric pressure)

Initial Stages: ignition to burnout

Launch Profile Thermal Loads

Heating of SV external surface (Solar Flux, Albedo, Earth IR, Aeroheating)



Free Molecular Heating in Ram Direction

Heating of LV external surface (Solar Flux, Albedo, Earth IR, Aeroheating)

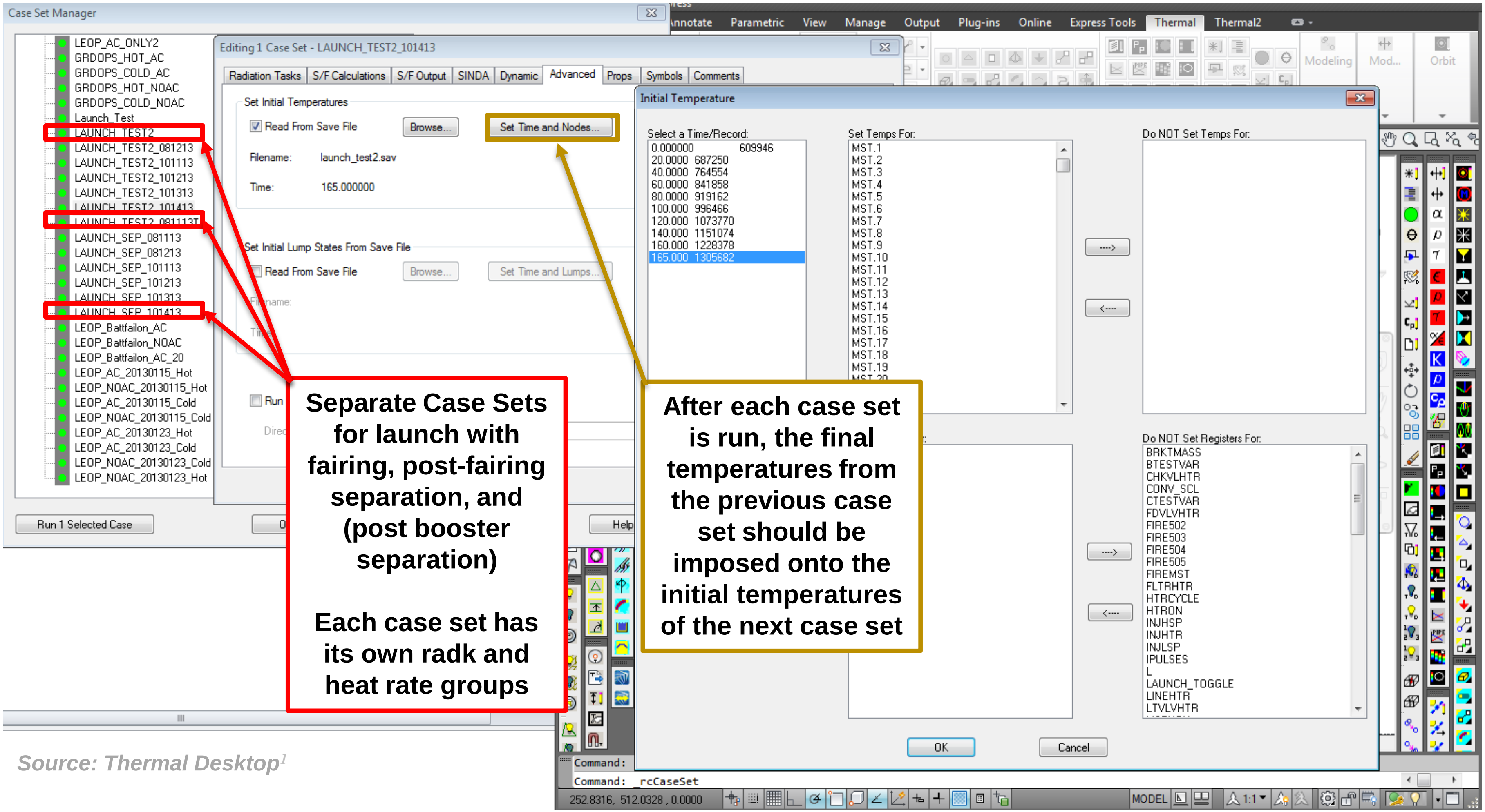
Launch Analysis Guidelines

- Analysis for launch vehicle aeroheating and other environmental effects typically performed by LV vendor
  - LV Vendor will provide temperature profiles of different components during launch and ascent phases
  - Inner fairing wall / inner acoustic blanket temperatures and motor soakback temperatures to launch adapter ring will be of interest to thermal engineer for SV analysis
  - Typically, for SV analyses during launch, can just set LV nodes to boundary temperatures provided by LV vendor’s analysis

- Therefore, thermal engineers typically concentrate on keeping the **spacecraft** within temperature limits during launch cases

Launch Analysis Case Setup

- Phases of launch analysis specified as **separate cases** in Thermal Desktop Case Set Manager



Source: Thermal Desktop[1]

Typical Launch Case Set Sequence

- For a basic launch and ascent phase, you will need to run these three cases sequentially to capture the entire launch profile:
   1. Pre-fairing separation

      Requires: SV internal radks, fairing internal radks, (convection to stagnant air)

      If LV vendor has already provided inner fairing temperature from their thermal analysis: impose it as a boundary temperature profile on all of the fairing nodes

      If previous LV thermal analysis has not been conducted by vendor: analysis requires external LV radks with environment, heat rates from launch trajectory (solar, Earth IR, albedo), *ablation model* (TD native code or external code) *aeroheating fluxes* (separate code)

      Runtime for this case: *from launch to fairing separation*

Typical Launch Case Set Sequence

2. Post-fairing separation with FMH and motor soakback

   Requires: SV internal radks, (LV booster stage internal radks), SV/LV external radks to environment, heat rates from launch trajectory, heat rates from FMH, motor soakback boundary temperatures imposed, final temperatures from Case 1 imposed onto initial temperatures for components common between Cases 1 and 2.

   Runtime for this case: *from fairing separation to last stage motor separation*

3. Post-spacecraft separation

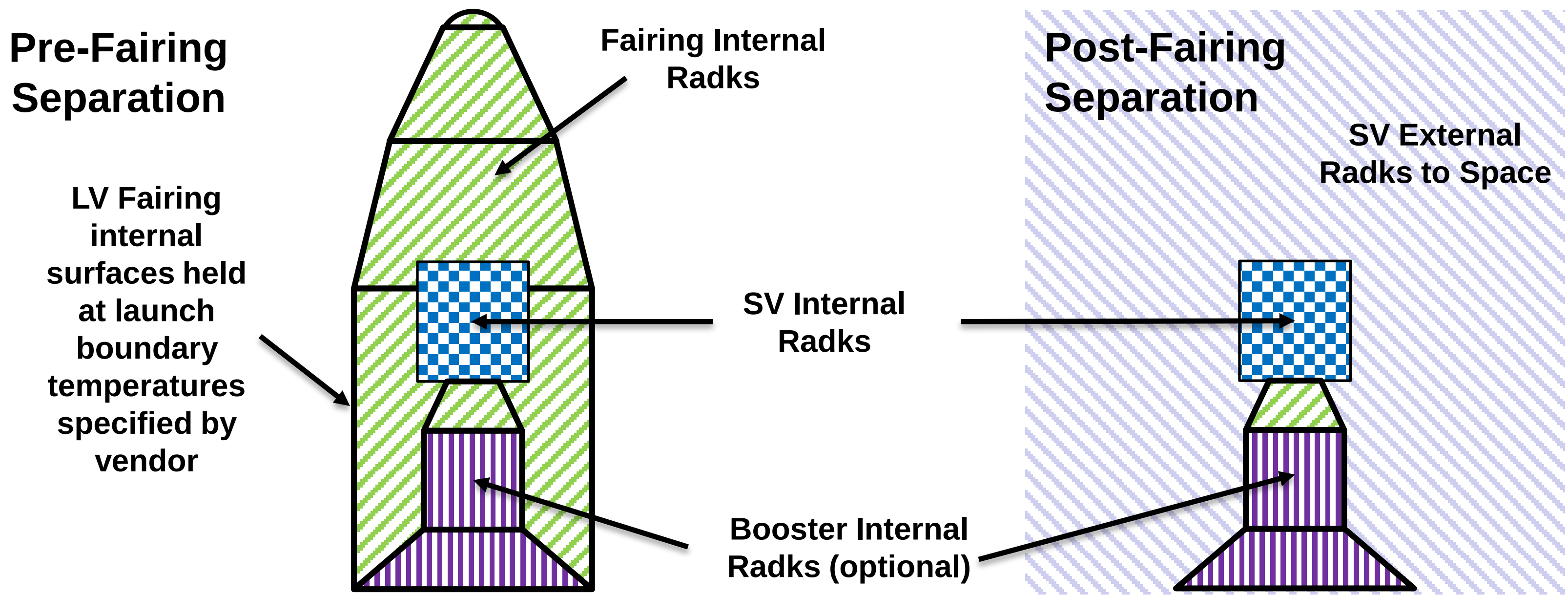
   Requires: SV internal radks, SV external radks to space, heat rates from checkout orbit environment, heatloads from spacecraft being powered on/component checkouts, final temperatures from Case 2 imposed onto initial temperatures for components common between Cases 2 and 3

   Runtime for this case: *from last stage motor separation to end of spacecraft checkout mission phase*

… now we will go over how to set up the radks and heat rates for these cases

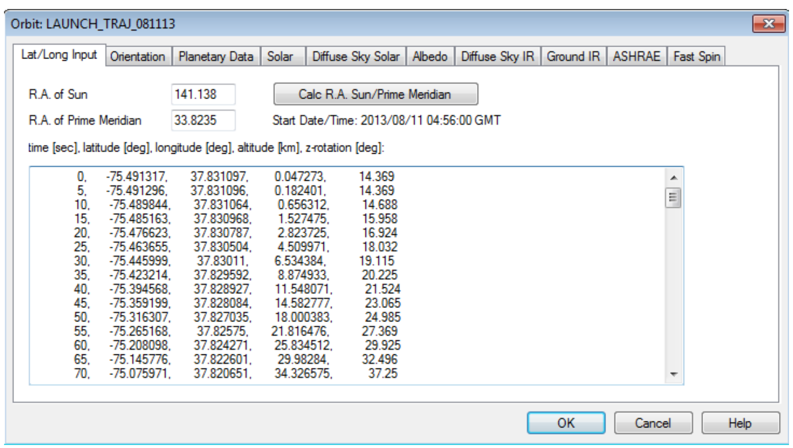
Launch Analysis Radks

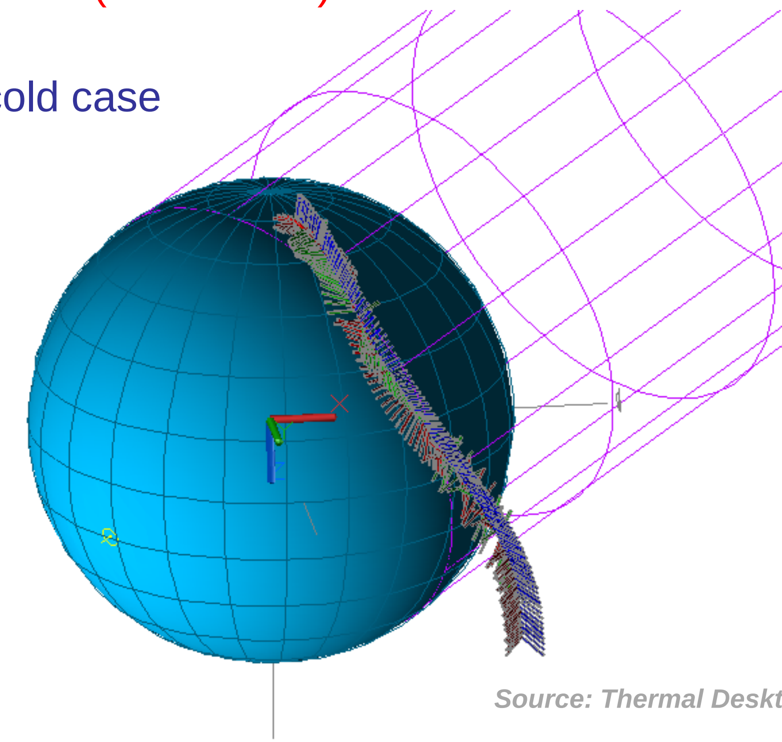
- Three typical Radk cases for launch sequence:
  - Pre-fairing separation case set should have radiation analysis group with internal fairing and spacecraft
  - Post-fairing separation case set should have radiation analysis group with spacecraft and booster motor internal and external views
  - Post-motor separation case set just has SV internal/external views



Launch Profile Heat Rates in Desktop

- For environmental heating due to launch trajectory, use Thermal Desktop Planetary Latitude/Longitude/Altitude List in Orbit Manager
  - Lat/Long Input: Use ACS subsystem-specified time vs. latitude, longitude, altitude, and z-rotation profile
    (z-rotation/roll profile is especially important for SVs with body-mounted solar panels and/or any unblanketed components, like radiators)
  - Hot Case: Use worst-case hot solar flux (1420 W/m^2).
    Cold case: Solar Flux = 0
  - Albedo: Use 0.35 in hot case, 0 in cold case





Source: Thermal Desktop[1]

Launch Profile Heat Rates in Desktop

- Additional Planetary Latitude/Longitude/Altitude List Parameters:
  - **Diffuse Sky Solar:** solar scattering due to atmospheric effects. Varies as a function of cloud cover or other effects. Can specify in model, **but normally this is only important to LV, not SV**.
  - **Diffuse Sky IR:** Hot Case: Use hottest diffuse sky temperature calculated from earlier. For Cold case: Use temperature of space (~3 K)
  - **Ground IR:** Use median Earth temperature (~298 K)
  - **ASHRAE Atmospheric Extinction Modeling:** calculates attenuated solar flux (solar flux lost to atmospheric effects) as LV ascends through the atmosphere
    - Defined by inputting values for extinction coefficient, cloudiness fraction, and fraction of solar scattering to calculate direct and diffuse solar fluxes (typical values can be found in ASHRAE handbook)
    - These values override those in Diffuse Sky Solar during launch
    - However, atmospheric extinction modeling **not as important for SV modeling**, only LV, since SV protected by fairing until upper atmosphere
  - **Fast Spin:** can be used to specify SV spin, but it is preferable that this is specified outright in z-rotation of Lat/Long input

Aeroheating and Ablation

- Aeroheating profile needs to be determined with separate code
  - Possible option is ITT Aerotherm's Aeroheating and Thermal Analysis (ATAC) Code[2]: generates tables of recovery enthalpies and heat transfer coefficients to integrate into Thermal Desktop with the following equation:

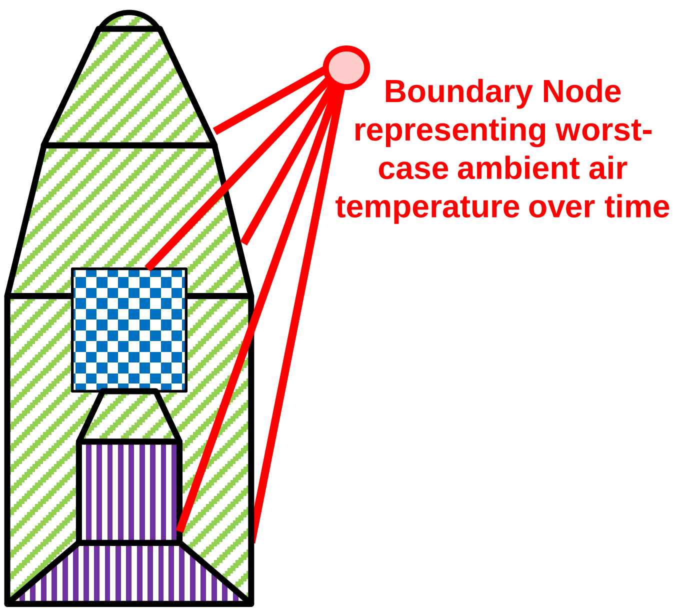
$$Q_{Aerothermal} = h(H_{rec} - H_{wall})$$

$Q_{Aerothermal}$	Aeroheating flux
h	Enthalpy film coefficient
H_{rec}	Adiabatic Wall Recovery Enthalpy
H_{wall}	Wall temperature air enthalpy

- Ablation of LV external surface can be calculated with native Thermal Desktop or other proven external codes
  - Native C&R Tech[1] code: ABLATE/ABLATERATE
  - MSFC ABL code[3], Orbital Sciences 1-D Cork Ablation Model[4], and AEROFAST 3D ablation model[5] are suitable alternative methods when added to SINDA/FLUINT thermal model

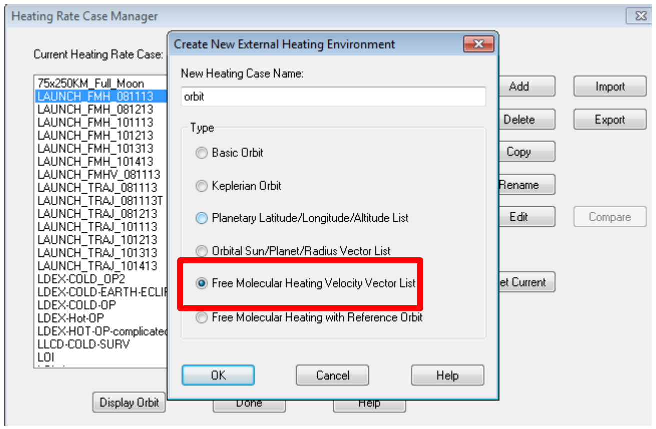
Convection to Stagnant Air

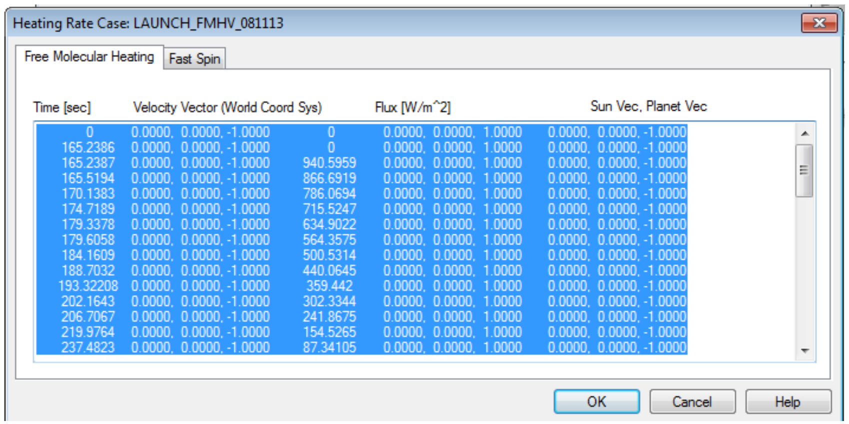
- Free convection to stagnant air during launch decays with decrease in atmospheric pressure
  - Depending on the fidelity of your model, you can **linearly or logarithmically decay convection coefficient over time** (vary conductance per area value of conductors from external surfaces to air temperature boundary node)
  - However, it may be more conservative to just ignore convection effects altogether in launch analysis



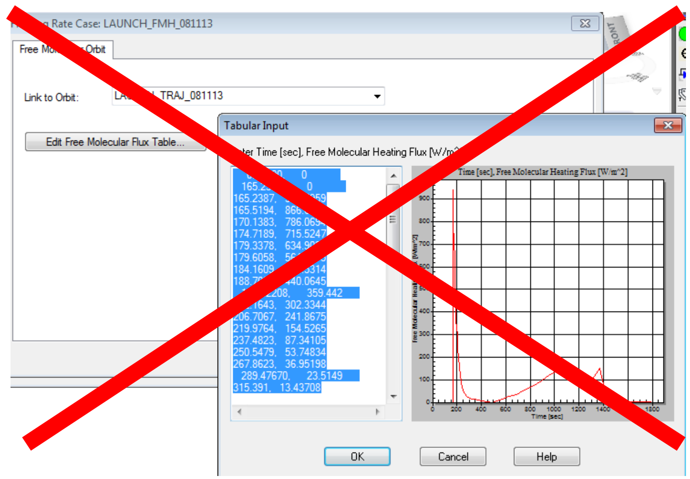
Free Molecular Heating (FMH)

- After fairing separation, SV experiences free molecular heating in direction of velocity vector
  - This is modeled as separate heat rate (in addition to the heat rate specifying trajectory): **Free Molecular Heating velocity vector list in Thermal Desktop**





  - Though Thermal Desktop has an option in the Orbits Manager for Free Molecular Heating with Reference Orbit, this **should not be used with a user-defined orbit** as it **will not work**



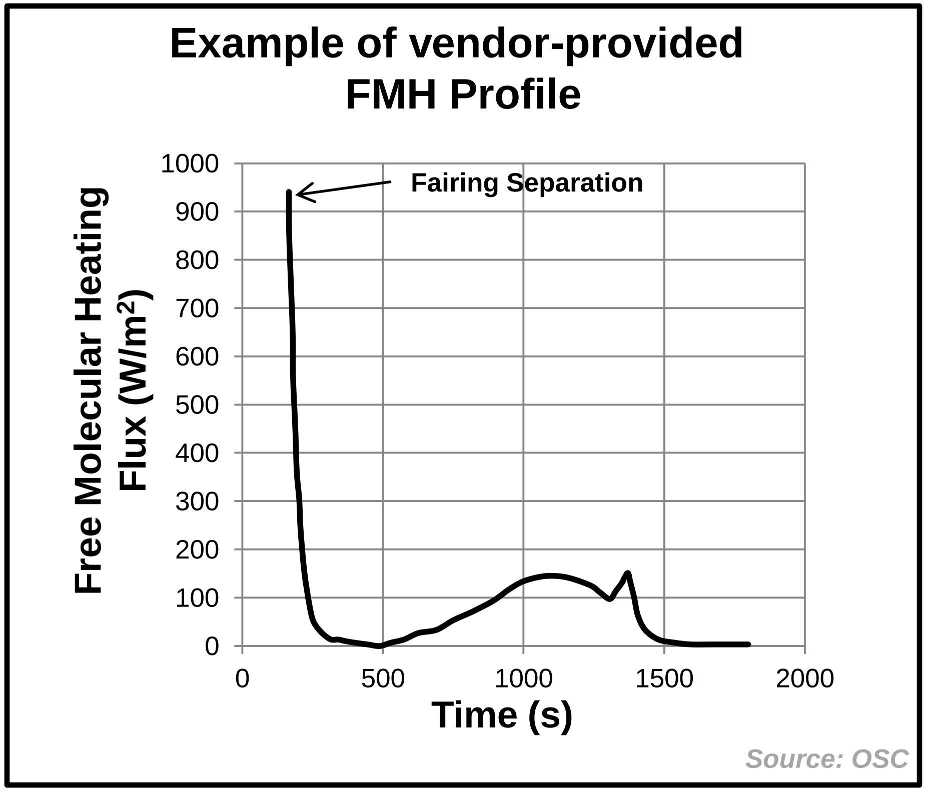
Source: Thermal Desktop[1]

Free Molecular Heating (FMH)

- FMH profile can be provided by launch vendor or can be assumed with simple calculations
  - Incident FMH fluxes affect all forward-facing surfaces which have a normal component to the velocity vector
  - FMH can be approximated simply by following equation:

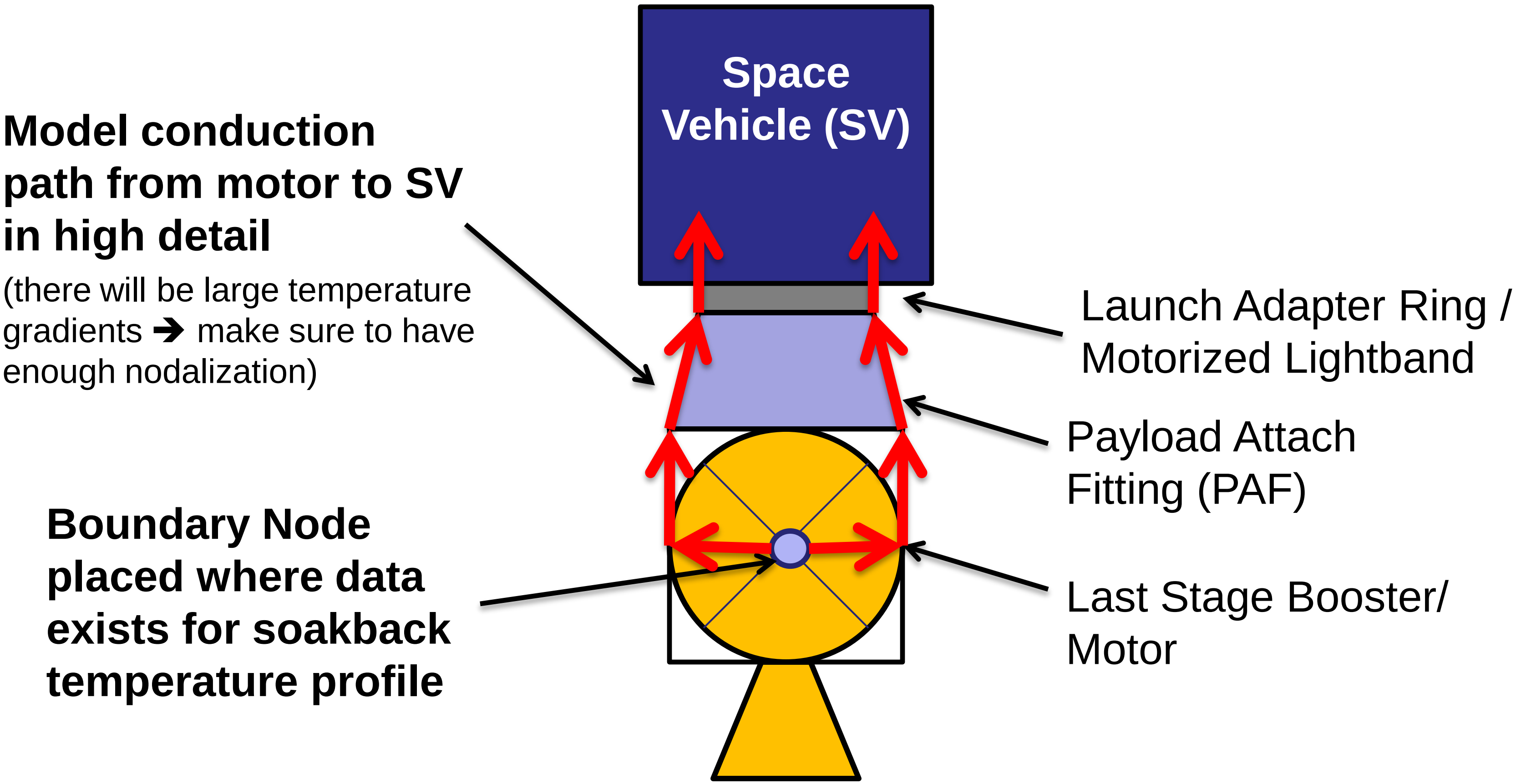
$$\mathbf{FMH} = \tfrac{1}{2}\rho v^3$$

ρ	Density
v	Velocity in ram direction

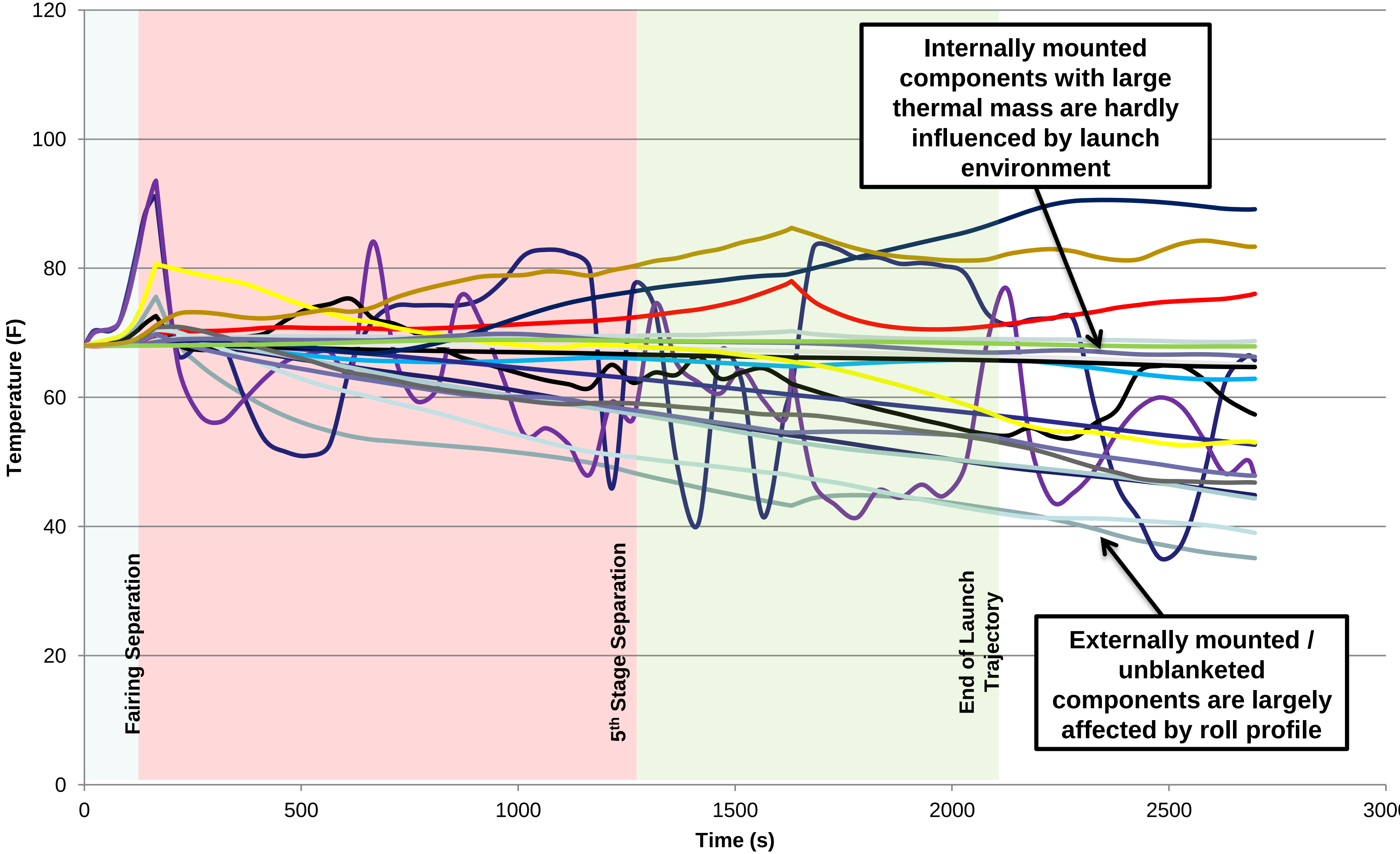


Motor Soakback Modeling

- The following is needed to accurately model soakback heating:



Example of Launch Analysis Results



Tips for the Wary…

- Always request thermophysical and optical properties early from the vendor, especially in cases where the Launch Vehicle specifications may be sensitive/ITAR-controlled.
- Do not assume external insulation optical properties are necessarily the coating that is on the launch vehicle. Often, launch vehicles have a separate, white or reflective coating.
- Daily variations in solar flux, ambient temperature, and diffuse sky temperature **must** be included in ground operations thermal model to obtain accurate, realistic results
- Before modeling, find out first from vendor which areas of LV are most sensitive to temperature changes, then add more detail in those regions
- LVs were built to withstand extremely high temperatures. If there are stringent LV requirements in ground ops, ask what is motivating those requirements

Major Takeaways from the Short Course

1. More detail is always better than less detail in launch model due to the number of factors that affect the LV and SV in ground operations. However, choose the level of detail you want to include based on the required fidelity for your analysis.
2. Launch analysis highly dependent on transient environmental factors (Diurnal Variations in air temperature and solar flux, FMH profile, launch trajectory, etc.). Therefore, make sure there are accurate profiles of these factors vs. time in your model.
3. Above all, always use common sense and good engineering judgment when looking at results to ensure that all factors are accounted for in your analysis and the solutions are physically sound

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Thank You

Questions?